Incorporating Occupant Behaviour and Comfort in Domestic Energy Retrofit

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Dedication

This thesis is dedicated to the memory of my mother Ping, a selfless woman whom I still miss every day.

Declaration

I, Hui Ben, hereby declare that this thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. Neither this, nor any substantially similar dissertation has been or is being submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University or similar institution. This thesis does not exceed 80,000 words for the Degree Committee of the Faculty of Architecture and History of Art.

Signed:

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Summary

While a large energy saving potential exists in domestic retrofit to meet the UK Government's goal of carbon emissions reduction through the Climate Change Act 2008, the complexity of occupant behaviour and comfort needs often prevents the seemingly achievable retrofit targets from being reached. These real-life complexities contrast starkly with the standardised and simplistic behavioural profiles currently used in energy modelling to generate retrofit recommendations. The provision of more detailed information concerning behaviour and comfort needs can help improve energy consumption predictions and enable policy interventions to respond to different household types while maintaining a comfortable indoor environment for occupants. This research combines both social and technical methods to develop a tailored approach for domestic retrofit using household archetypes. An archetype is a typical example of households sharing similar behavioural patterns and dwelling physical characteristics. On the one hand, it uses first-hand interviews and household surveys to understand people's social practices and patterns of behaviour. From these surveys, key household types based on household behaviours and dwelling characteristics are identified. On the other hand, the energy performance of buildings is monitored, and a model is developed incorporating these distinct household types to determine energy use. This modelling increases the accuracy of predictions concerning which retrofit strategies are most effective for each household type. The use of household archetypes to analyse energy and cost implications can bring about significant savings compared to the conventional approach, which treats occupancy and behaviour in a homogeneous manner. Overall, this research suggests that a tailored approach, incorporating human behaviour, to domestic retrofit can considerably improve energy savings without compromising occupant comfort.

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CHAPTER 1 INTRODUCTION

> The biggest gains, in terms of decreasing the country's energy bill, the amount of carbon dioxide we put into the atmosphere, and our dependency on foreign oil, will come from energy efficiency and conservation in the next 20 years. Make no doubt about it. That's where everybody who has really thought about the problem thinks the biggest gains can be and should be.
>
> – Steven Chu, *U.S. News & World Report*

There is general recognition that the “energy efficiency first” principle applies to all policy-making and investment decisions. However, energy savings from improved energy efficiency in buildings often fall short of expectations. This research on this multi-faceted problem focuses on solving one part of the problem: the effectiveness of energy retrofit strategies associated with occupant behaviour and their comfort needs.

This thesis contributes to the development of energy efficiency design and policy. It proposes a methodological framework for more effective carbon emissions reduction in existing buildings compared with the conventional approach. While climate change is at the heart of the problem, it is people that matter the most as people use energy, not buildings (Janda, 2011). Therefore, this research sets out to examine the role of occupants in influencing the effectiveness of retrofit strategies. It starts by exploring household energy and comfort practices, followed by developing household archetypes for better retrofit solutions in a UK context. The findings also enable more accurate energy-saving predictions and more reliable retrofit recommendations. The outcome of this research will aid a transition towards more effective retrofit strategies and programmes.

1.1 Research Background

Climate change is one of the greatest threats facing humanity. It is caused by the accumulation of carbon dioxide (CO_2) in the atmosphere, leading to an increase in average global temperatures. The Kyoto Protocol was adopted in 1997 as the first legally binding agreement linked to the United Nations Framework Conventions for Climate Change (UNFCCC), setting out carbon emission limitations and commitments for 192 countries across the world (UNFCCC, 1998). In 2015, 195 member nations of the UNFCCC reached the Paris Agreement at Conference of Parties (COP) 21, with a commitment to limit the increase in average global temperature to well below $2^{o}C$ as well as limiting the temperature increase to $1.5^{o}C$ above pre-industrial levels (UNFCCC, 2015). The UK is at the forefront of low-carbon development strategies and has passed the Climate Change Act (2008) – the first legally binding national framework with the goal of cutting carbon emissions by at least 80% by 2050 (compared to a 1990 baseline) (HM Government, 2011; DTI, 2007). To achieve this goal, the Government has developed a set of policies and schemes to encourage the delivery of energy efficient measures and savings across all sectors (DECC, 2014).

Retrofitting buildings presents a great opportunity for CO_2 emissions reduction, energy conservation and improvements in building performance (Climate Change Act, 2008). In particular, domestic buildings account for 29% of the UK's total energy consumption, and are therefore one of the most important areas being targeted by the Government (DTI, 2007; DECC, 2014). Given the extremely low replacement rate of the existing housing stock, approximately 80% of current dwellings will still be in use in 2050 (Power, 2008; Ravetz, 2008; Communities and Local Government Committee, 2008). The UK's housing stock of approximately 27 million homes is amongst the least energy efficient in Europe, leading to higher energy bills as well as negative environmental and health impacts (Committee of Public Accounts, 2016). For example, reports (Washan, 2012; Vaze, 2014) show energy efficiency can permanently reduce energy bills by £300 each year and lift 9 out of 10 homes out of fuel poverty. In addition, an estimated 34,300 excess winter deaths occurred in England and Wales in 2016-2017 (Office for National Statistics, 2017) and around 30% of these were due to cold homes (World Health Organisation, 2011). Many such deaths could be prevented through warmer housing (H.M. Government, 2010b). Thus, improving the energy efficiency of existing housing would not only reduce the UK's carbon footprint and energy consumption, but would also significantly benefit all occupants.

The government has introduced various retrofit policies and programmes to encourage wider uptake of energy efficiency measures. In particular, there has been a range of schemes, regulations and guidance to assist landlords, homeowners and housing associations to deliver low-carbon dwellings. For example, the Energy Saving Trust and Carbon Trust provide impartial advisory services to raise awareness among homeowners of their options for retrofit (Stafford et al., 2011). In addition, Energy Performance Certificates (EPC) – introduced as a requirement of the European level Energy Performance of Buildings Directive – are required by law to be provided by owners when they sell or rent out a home (DCLG, 2011). The certificates inform the new buyers or tenants about energy use and retrofit options. Government supported product-labelling initiatives also play a part in raising awareness of the most energy efficient products on the market. Moreover, the Energy Efficiency (Private Rented Sector) (England and Wales) Regulations 2015 have brought Minimum Energy Efficiency Standards (MEES) into force from April 2018, making it unlawful to let properties with an EPC rating of 'F' or 'G'.

The introduction of energy efficient technologies has often failed to bring the promised reduction in domestic energy use or CO_2 emissions. This phenomenon is commonly labelled "performance gap" or "rebound effect" where occupants offset the savings from improved energy efficiency by increasing their consumption (Sorrell et al., 2009; de Wilde, 2014). The efficiency measures targeting building fabric or systems such as wall insulation or a boiler upgrade allow occupants to maintain comfort levels without necessarily modifying their behaviour in any way. However, research shows that occupant behaviour towards space heating has changed over the past forty years, manifested as an increase in mean indoor temperatures in winter (Palmer and Cooper, 2013; Mavrogianni et al., 2013). The rebound effect has occurred in space heating use, too, where there has also been an increase in the thermal comfort of occupants (Greening et al., 2000). This might be explained by adaptive thermal comfort, which recognises that people's expectations for indoor temperatures can differ and evolve over time (Nicol and Humphreys, 2002; Chappells and Shove, 2005). User practices are not static, and technical standards as well as norms developed for building energy efficiency may even foster higher social norms of comfort and subsequently higher consumption (Shove, 2003a). Exploring opportunities associated with adaptive thermal comfort is arguably vital in the context of climate change and could potentially offer new approaches to tackle energy demand reduction.

Space heating has remained the dominant use of energy in homes since 1970 (Palmer and Cooper, 2013). Meanwhile a majority of dwellings in England have poor insulation or inefficient heating systems (DCLG, 2009). Consequently, it is vital to implement home improvements that reduce heating consumption. This can also include energy conservation measures that encourage behaviour change towards lower consumption. Research shows potential energy savings from behaviour change can far exceed those from physical improvements (Ben and Steemers, 2014). Hence, it is important to understand how user practices, needs and satisfaction contribute to residential energy demand as well as occupant flexibility to change.

Energy conservation actions in the home encourage behaviour change on the part of the householder. For example, a major government initiative is to equip all UK homes with smart meters by 2020. Smart meters are a socio-technical feedback intervention, as the government believes that by providing householders with real-time direct feedback, they will gain a greater understanding of their energy use and greater control over how energy is consumed in their home. The success of this relies heavily on householders' engagement with the interface and their attitude towards financial savings and/or conserving energy. The effectiveness of smart meters in energy conservation on a long-term basis is as yet unknown as research is still in the early stages, but it is clear that in order to achieve behaviour change on a national scale, the government cannot afford to be purely device-orientated; it must understand the socio-psychological aspects of behaviour towards energy technologies (Boardman, 2004; COI, 2009; Darby, 2006; Lutzenhiser, 1992).

Occupant behaviour has been demonstrated to have a significant impact on building energy performance. The size of this effect may be large, varying energy usage by a factor of two or more (Baker and Steemers, 2000; Gram-Hanssen, 2004; Karlsson and Moshfegh, 2007; Santin et al., 2009; Gill et al., 2010; Steemers and Yun, 2009; Santin et al., 2013). In addition, the predicted energy savings associated with energy efficient technologies frequently exceed actual savings made due to behavioural factors (Branco et al., 2004; Cole et al., 2008; Blom et al., 2011; Gram-Hanssen et al., 2012; Galvin and Sunikka-Blank, 2013). These behavioural factors may be categorised as socio-economic variables (Santin et al., 2009; Steemers and Yun, 2009), lifestyle choices and socio-material configurations (Gram-Hanssen, 2010). They may also be explained by modelling and technological operational errors (Stern, 1985), as well as by a rebound effect relating to higher comfort expectations (Sorrell et al., 2009). Within a socio-technical approach this is taken further to show how occupant comfort co-evolves with technical systems in a social and cultural context (Shove, 2003a & b; Guy, 2006).

1.2 Statement of the Problem

The goal of energy retrofit is to reduce energy consumption and carbon emissions effectively, which is currently undermined by the under-realisation of retrofit potential related to occupant behaviour and comfort issues. From a technical perspective, the approaches often lie in making energy models which can either be used for prediction or for optimising technologies in the design phase (Brohus et al., 2009; Page et al., 2008; Rijal et al., 2008). For example, a set of standard comfort conditions have been designed to match physiological needs, such as 'thermal, air quality, visual, acoustic, ergonomic, and psychological comfort' (ASHRAE, 2010), resulting in the provision and maintenance of a fixed set of physical conditions (Cole et al., 2008). However, this neglects the social and behavioural dimensions of comfort, which are also important. From a social science perspective, the primary focus is on describing and understanding households' energy consumption related to comfort (Shove et al., 2008). This is done using segmentation and lifestyle approaches and socio-economic understanding, as well as practice theory (Warde, 2005; Strengers, 2011; Hargreaves, 2011; Gram-Hanssen, 2010). For example, practice theory focuses on the collective and structural elements of what people actually do or say. These elements include technologies, competences and meanings (Shove, 2003a) and have primarily been explored in qualitative studies thus far. Consequently, the technical scientific approach and the social science approach have been considered separately from each other. Hence, the combination of both qualitative and quantitative analyses has been lacking.

There is a need to couple the understanding of occupants and their comfort needs with the effectiveness of retrofit technologies. Current retrofit guidance and recommendations are largely derived from the approaches that adopt standardised assumptions of occupant behaviour and comfort needs. This often leads to failed promises on energy savings and thereby generates mistrust. More accurate predictions are thus crucial for helping occupants make better-informed decisions and enabling a better design of retrofit programmes with more realistic targets.

1.3 Research Aim and Objectives

The aim of the present research is to develop a modelling approach that optimizes home energy retrofits, taking into account occupants' behaviours without compromising their comfort. This will enable the development of retrofit design and policy that can increase energy savings while maintaining occupant comfort.

The main objectives of this work are:

- To explore the social practices of occupant comfort in the context of home energy demand;
- To develop household archetypes based on variables related to various social practices of comfort and consumption;
- To evaluate the impact of household archetypes on energy savings from retrofits.

1.4 Research Questions and Hypothesis

This research is designed to answer the following questions:

- How occupants carry out social practices of comfort in the home?
- What are the household archetypes?
- To what extent do household variations have an impact on the effectiveness of retrofit measures?

The hypothesis is that if retrofit strategies are tailored to household archetypes, the results will increase energy savings without compromising occupant comfort.

1.5 Thesis Structure

This thesis comprises eight chapters (Figure 1.1). The purpose of each chapter is outlined below. The present chapter has defined the problem, identified the gap in existing knowledge, and outlined the aim of the research.

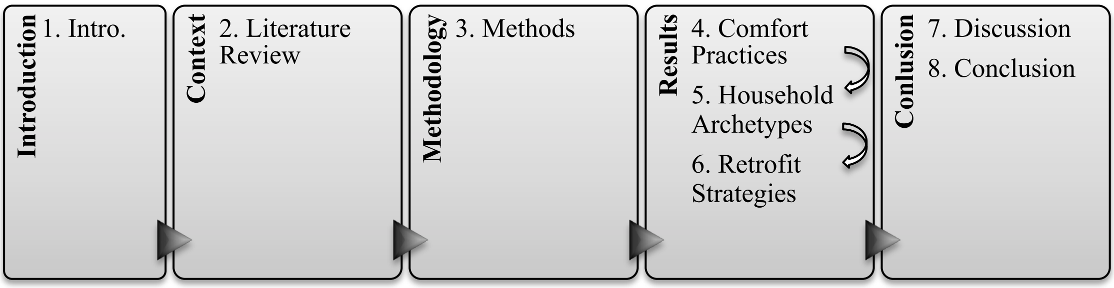


Figure 1.1 Structure of chapters in this thesis

Chapter 2 is a literature review that sets the scene for the forthcoming research. It provides a summary and synthesis of key literature, locating current research within the context of existing literature.

Chapter 3 presents the methodology that sets the research philosophy and approach, providing rationale for the practical implementation of the design. It details the data collection and analysis methods, together with their overall validity and ethics of the research.

Chapter 4 describes the results obtained from exploring household comfort practices. It generates the hypothesis and derives a set of themes with a social practice approach, laying the foundation for developing the survey instrument in the quantitative research phase.

Chapter 5 develops household archetypes based on statistical analyses of data collected from a household survey. The analyses determine behavioural patterns, as well as their relationship with household and dwelling characteristics.

Chapter 6 assesses the impact of a modelling approach that incorporates the distinct household types derived above. The effectiveness of this approach is modelled and compared with that of a conventional method such as the Standard Assessment Procedure (SAP) used for generating EPC. The results show that the new approach can more accurately predict which retrofit strategies are most effective for each household type.

Chapter 7 discusses the significance and implications of the findings in light of the existing knowledge about the under-realisation of retrofit potential, occupant behaviour and comfort. It also explains new insights taking the findings into consideration.

Chapter 8 concludes the thesis with a recapitulation, while providing recommendations for future research.

1.6 Summary

This research argues that the incorporation of occupant behaviour and comfort in a retrofit strategy will significantly improve its effectiveness and reliability in addressing the under-realisation of retrofit potential. Drawing on both qualitative and quantitative approaches, it develops a realistic way of improving energy savings while maintaining occupant comfort from domestic retrofits. This begins by exploring household energy and comfort practices, identifying key variables to create a survey instrument. Then it derives distinct household types based on behavioural patterns and household and dwelling characteristics. Finally, it demonstrates the significant impact of household archetypes on energy savings and the effectiveness of retrofit strategies, compared with the conventional method used in EPC. Based on the synthesis of results, this research proposes a set of recommendations to improve the energy retrofit design and policy.

CHAPTER 2 LITERATURE REVIEW

2.1 Preamble

While a large energy saving potential exists in domestic retrofit to meet the Government's goal of a reduction of carbon emissions, the intricacies of occupant behaviour and comfort needs often prevents the seemingly achievable retrofit targets from being reached. This phenomenon has been studied extensively, under various terms such as energy performance gap, comfort take-back, rebound and prebound effects. An analysis of this discrepancy between measured and predicted energy savings from retrofit suggests the gap can be up to 50% (Sanders and Phillipson, 2006). Meanwhile, studies show that energy use can vary by a factor of two or more in identical buildings depending on occupant behaviour (Seligman et al., 1978; Baker and Steemers, 2000; Steemers and Yun, 2009; Gram-Hanssen, 2010; Larsen, et al., 2010; Yao, 2013).

The design of energy efficiency upgrade in existing housing is commonly predicated on assumptions of standardised occupant behaviour at home. Meanwhile, a ubiquitous 'fabric-first' approach to retrofit is advocated for its ability to reduce energy loss through the building envelope. However, with the identification of significant behavioural influence on energy use and development of energy saving technologies, would such conventional retrofit guidance still be appropriate for optimal energy demand reduction?

It is demonstrated that occupant behaviour has a larger energy saving potential than the physical improvement of a dwelling alone (Ben and Steemers, 2014). In particular, setting the heating temperature has the highest impact on energy use. However, encouraging occupants to turn the heat down and thereby reduce energy use cannot succeed without addressing comfort issues.

Maintaining a comfortable indoor environment has been a major driver for the provision of heating, ventilation, air conditioning (HVAC) and various other building technologies, which in turn stimulate energy demand. The constitution and levels of comfort evolve over time and differ from person to person. Sociotechnical, psychological and physiological diversities lead to a divergence of comfort practice and optimal conditions. The availability of individual thermostats allows householders to enjoy personalised indoor temperatures, which often deviate from those that have been assumed in modelling simulation and design. It is one thing to appreciate the technical optimisation of comfort and energy use, but quite another to celebrate individual differences and their implications for retrofit.

The complexity of occupant behaviour and comfort needs in real life forms a stark contrast to the standardised and simplistic behavioural profiles assumed in the energy modelling used to generate current retrofit recommendations. The existing sophisticated occupant behavioural modelling, however, has not been well integrated into retrofit applications (Jia et al., 2017). The guidance used in domestic retrofit is often solely based on dwelling physical characteristics, while neglecting the varying needs of inhabitants. Consequently, any decision for an energy efficiency upgrade of a house is dissociated from the interactions between occupants and dwelling, and from personal comfort preferences on top of that. This dissociation presents itself as an important knowledge gap in domestic retrofit research and applications.

Extensive literature exists in the field of energy efficiency and occupant behaviour, which can be broadly divided into technical science (Yun and Steemers, 2011; Brohus, et al., 2009; Page, et al., 2008; Rijal, et al., 2008) and social science perspectives (Shove et al., 2008; Warde, 2005; Strengers, 2011; Hargreaves, 2011; Gram-Hanssen, 2010). The integration of the two approaches is however far more complex, compounded by indoor comfort issues which have an important bearing on the problem at hand. This literature review critically evaluates these overlapping subjects through linking them together to identify any gaps while contextualising current research.

2.2 Comfort in Buildings

The origin of comfort is associated with strengthening, support or consolation. Due to the invention of air conditioning and heating systems during the twentieth century, it became possible to control indoor conditions where the concept of comfort started to have strong physical and environmental connotations. The science of comfort developed in recent decades has been centred on the demand for better environmental conditions through a wide use of heating, ventilation and air conditioning (HVAC) systems (Fabbri, 2015). Approached with the principles of thermodynamics, thermal comfort was parameterised and standardised using engineering calculations. It became marketed as a product, produced by technologies marked as one of the most energy intensive aspects of modern lifestyles (Cooper, 2008). The growing reliance on air conditioning further increases energy demand and CO_2 emissions, forming a trajectory that is ultimately unsustainable (Chappells and Shove, 2005). It is therefore an appropriate time to review the concepts of comfort and their implications for domestic energy conservation.

2.2.1 Comfort and Energy

The meaning of comfort is contested and fluid, depending on the social context (Shove et al., 2008). From a historical perspective, what comprises comfort has changed drastically over centuries, which has arguably to do with technological developments (Giedion, 1948). Consumer culture has pushed forward the material aspect of comfort, brought in as a middle ground between necessity and luxury (Crowley, 1999). The idea of comfort has thus been reinvented through a combination of culture and technology, providing a platform for respectability yet satisfaction in consumer practices. Common elements can be found in defining comfort as: 1) a subjective personal state; 2) affected by a combination of physical, physiological and psychological factors; and 3) a reaction to environment or situation (de Looze et al., 2003).

Zooming in to the domestic realm, comfort often goes hand in hand with the idea of home. Rybczynski (1986) placed comfort in the centre of his discussion about the design of a home, where comfort consisted of convenience, efficiency, leisure, ease, pleasure, domesticity, intimacy and privacy. Heijs and Stringer (1987) classified residential comfort into social-psychological aspects as well as physiological needs. Pineau (1982) obtained four elements of comfort, ranked in order of importance: personalisation, freedom of action, space and warmth.

With respect to building energy use, however, comfort research has mainly focused on quantifying indoor environmental quality to comply with specified standards and design codes. Viewed from this perspective, the understanding of comfort is very much limited to the environmental sphere (Mauro and Santos, 2011). Despite being recognised as 'a state of mind' (Rohles, 1988; Goldman, 1999), comfort is pursued as an attainment, seemingly achievable by a combined set of environmental parameters. However, this conventional application of fixed comfort standards would inevitably lead to a future of unsustainable energy use (Baker, 1993).

Heating accounts for the lion's share of total household energy consumption (BEIS, 2018), and largely contributes towards occupants' thermal comfort. Studies on thermal comfort therefore have important energy use implications. The recent development of adaptive approach to thermal comfort standards has led to less energy intensive criteria by recognising a wider range of indoor thermal environment that satisfies occupants (Nicol and Humphreys, 2002). Meanwhile, a variety of factors may influence occupants' heating behaviours such as the choices of heating temperature and duration. These factors can be classified as: environmental factors (e.g. humidity), building and system related factors (e.g. type, age and size of dwelling), occupant related factors (e.g. age, gender, culture/race, education level of occupant) and others (e.g. time of day or week, heating price) (Wei et al., 2014). For example, research into the rebound effect showed that households increased their heating temperature after energy renovation of their dwellings (Hong et al., 2009), which explained why no reduction in energy use was observed following the upgrades (Hong et al., 2006). Therefore, it is important to address the behavioural component while pursuing a comfortable low-energy environment.

2.2.2 Engineering Comfort

Comfort began to be related to order and control of one's immediate surroundings when mechanisation made all the relevant technical aids available (Giedion, 1948). The invention and development of HVAC systems has particularly changed the way we use and operate buildings, as well as how comfort is perceived and expected. Since this technological revolution, thermal comfort has become the predominant subject in indoor comfort research. Extensive studies in this area have contributed to the specifications for international standards (i.e. ANSI/ASHRAE Standard 55, EN 15251, ISO 7730) that define the ranges of acceptable indoor environmental conditions.

Beginning with the military requirements in the early twentieth century, laboratory experiments on the relationship between the human body and environment laid the foundation for physiologically based comfort models (Fabbri, 2015). These models apply the first law of thermodynamics to the human body to maintain the core temperature steady at around 37^{o}C. To retain homeostasis in a non-thermoneutral zone, heat exchange must happen involving conduction, convection, radiation and evaporation. Various thermal physiological models have been developed from a numerical view, such as the one-node model (Givoni and Goldman, 1971), two-node model (Gagge et al., 1971; Azer and Hsu, 1977), 40-layer finite difference skin model (de Dear and Ring, 1990), and multi-node model (Fiala et al., 1999, 2010; Huizenga et al., 2001).

With the recognition of thermal sensation being both physiological and psychological, evaluations of subjective responses were added to the comfort model equation. The first and one of the most influential researchers in this field was P.O. Fanger, who introduced the Predicted Mean Vote – Predicted Percentage Dissatisfied (PMV-PPD) model (Fanger, 1970). PMV allows people to express their thermal sensation through a scale from Cold (-3) to Hot (+3), whereas PPD determines the percentage of thermally dissatisfied people. This model is arguably the most widely used tool for designing and assessing indoor comfort. It is a steady-state model and best suited to air-conditioned spaces. In addition, other models have been developed to better predict occupant thermal sensation and comfort in asymmetrical conditions (Cheng et al., 2012), such as the UC Berkeley Thermal Comfort Model (Arens et al., 2006), Dynamic Thermal Stimulus Model (de Dear et al., 1993) and Dynamic Thermal Sensation model (Fiala et al., 2003 & 2010).

The quantification of comfort by way of modelling has enabled designers and engineers to define environments with a certain degree of accuracy (Shove, 2000). This has to a large extent been driven by the development of the air conditioning industry (Brager and de Dear, 1998). It aims to create comfortable conditions that are universally acceptable. However, empirical research has shown that people can tolerate or be satisfied with a much wider range of environments compared with what the model-based standards suggest. Rather than having narrowly defined limits, this opens up opportunities for passive design in naturally ventilated or mixed-mode buildings.

2.2.3 Adaptation

Adaptive comfort theory has been established through field studies that acknowledge the real world complexities as an alternative to the traditional heat balance model based on controlled laboratory experiments. Rather than being fixed and universal, indoor comfort temperature is seen as related to outdoor climate (Humphreys, 1972; Humphreys, 1995; Nicol, 1995; de Dear and Brager, 2001). Instead of positioning occupants as passive recipients of thermal stimuli, the adaptive approach views occupants actively engaging with the environment and creating their own comfort preferences (de Dear and Brager, 2001). By the adaptive principle, occupants' thermal expectations and preferences vary according to contextual factors and past thermal experiences (de Dear and Brager, 1998a). People with more opportunities to adapt either through themselves or the environment will be less likely to experience discomfort (Nicol and Humphreys, 2002).

Various adaptive processes happen through behavioural, psychological and physiological adjustments (de Dear and Brager, 1998a). Behavioural adaptation is manifested by people actively managing their environments or personal circumstances such as operating HVAC controls, adjusting clothing, changing locations or scheduling activities (de Dear and Brager, 1998b). Psychological adaptation denotes the way one's perception is altered, with several key factors identified: naturalness, expectations, past experience, time of exposure, perceived control and environmental stimulation (Nikolopoulou and Steemers, 2003). Physiological adaptation happens as gradual physiological responses to external stimuli to maintain homeostasis. The physiological acclimatization forms over the long term and applies mostly to extreme conditions, whereas both behavioural and psychological feedbacks have a much more significant influence on restoring comfort in buildings (de Dear and Brager, 1998b).

An adaptive approach to comfort has led to an update in international standards (i.e. ANSI/ASHRAE Standard 55, EN 15251, ISO 7730) for buildings without air conditioning to have acceptable temperature ranges based on field surveys. This allows for a wider variety of possible indoor environments, in which thermal variation can also bring positive delight (Heschong, 1979; Cabanac, 1971; de Dear, 2011). This has further implications on building design and operation, where both improved comfort and lower energy use can be achieved in mixed-mode buildings (Borgeson and Brager, 2011). Instead of fine-tuning the air temperature to an optimum, buildings need to provide adaptive opportunities that enable inhabitants to make themselves comfortable in a sustainable manner (Nicol, 2011). Brager et al. (2015) proposed five ways to provide enhanced thermal experiences, including "shifts from centralized to personal control, from still to breezy air movement, from thermal neutrality to delight, from active to passive design, and from system disengagement to improved feedback loops."

Adaptation shows that occupant comfort is constructed as a balance between the indoor conditions at the time and thermal expectations resulting from past experiences, cultural and technical practices (de Dear, 1994). In this way, the adaptive process, such as how comfort is perceived and practiced, is as crucial as the technical arrangements involved. In other words, while relevant standards and technologies direct the way a comfortable indoor environment is provided, they co-evolve with the understanding and practice of comfort. Thus it is the recognition and incorporation of the mutual influence between inhabitants and sociotechnical regimes that can drive sustainable development without compromising the users' comfort.

2.2.4 Co-evolvement

Comfort is a contested and controversial concept captured in a variety of disciplines. It has been conventionally the subject of much research in the engineering and building sciences, which aims to define and understand the physiological and psychological parameters of comfort to determine the optimal conditions by means of optimising comfort through specifying technologies and buildings (i.e. Brager and de Dear, 1998; Humphreys, 1976; Oseland and Humphreys, 1994). These studies tend to focus more on optimising the physical indoor conditions, and less on understanding behavioural aspects such as individual attitudes and motivations addressed in social sciences. Meanwhile, researchers in social sciences (i.e. Shove, 2003a; Warde, 2005; Gram-Hanssen, 2010) view comfort from a practice perspective, comprised of knowledge, rule, meaning, and technology. Such a view explores how ideologies and technologies of comfort have co-evolved with society, suggesting that comfort is as much a cultural phenomenon as a technical innovation (Chappells and Shove, 2005).

Contributions to producing comfort conditions in buildings are abundant. These construct comfort as “the provision and maintenance of a fixed set of thermal, luminous and acoustic conditions” (Cole et al., 2008). Such a view tends to focus on defining and refining the biological, physical and physiological aspects of comfort, and tends to focus less on the role of cultural and social conventions in at least partially producing these judgments of comfort. “Comfort in buildings should be considered as the absence of long-term extreme values of environmental comfort parameters, rather than the maintenance of precise and close limits.” (Baker and Steemers, 2000) Comfort – or, rather, the absence of discomfort (Brager and de Dear, 2003) has been tested in relation to “a number of parameters including air temperature, mean radiant temperature, relative air velocity and vapour pressure in ambient air, participant activity level, thermal resistance of clothing (i.e. Fanger, 1973), humidity, air quality, (day) light and noise (i.e. Jaffari and Matthews, 2009). Each of these parameters may be adjusted and regulated using a suite of technologies including windows, radiators, thermostats, controls and insulation” (Hinton, 2010).

In this engineering-based way of understanding, comfort is presumed to be a definable human condition in the design of buildings and technologies; as such, it has come to structure the way we think about, practise and experience comfort (Jaffari and Matthews, 2009). However, such an established array of parameters to provide comfort has been critiqued for ignoring varied ways in which individuals may practise comfort, where the parameters are standardised in the technological provision of comfort as a universally experienced physiological need. Cole et al. (2008) argue that the conventional realm of comfort provisioning has tended to emphasise the combination of building and systems enveloping the occupants, ignoring most behavioural aspects of comfort, thus effectively treating occupants as the passive recipients of the conditions without considering the social interactions between humans and their physical environment. This increasingly institutionalised approach to comfort has led to a prescribed set of more-or-less universal defined environmental parameters, independent of the dynamic of occupants, in order to maintain a stable indoor environment despite weather conditions outside (Shove, 2003a; Shove, 2006). According to Brager and de Dear (1998), occupants adapt to their environment actively in interacting with the 'person-environment system'. Here, variable indoor temperatures may be associated with increased occupant comfort, in contrast to static environments (Nicol and Roaf, 2005).

Whilst engineering-based comfort provision tends to focus on optimising the physical conditions in a given indoor environment, several scholars have suggested that these physical conditions may need to be relatively flexible as a wide range of comfort expectations exist amongst different individuals (i.e. Nicol and Roaf, 2005; Leaman and Bordass, 2007; Cole et al., 2008). Variety in indoor temperatures may be related to individual preference or the utilisation of relatively less energy intensive means to achieve comfort by personal control rather than the physical conditions given (Hinton, 2010). Individual comfort preferences may be associated with factors such as climate, thermal expectations and adaptation (Fountain et al., 1996), in addition to psychological, behavioural, social and contextual factors (Cole et al., 2008). According to Cena et al. (1990), behavioural norms and perceptions of comfort are influenced by local climatic and socioeconomic conditions. Critchley et al. (2007) discovered that a quarter of participating households were typically run at lower temperatures than the government's recommendation, which related at least in part to adaptation to (or preference for) lower temperatures. Leaman and Bordass (2007) found that occupants can either passively or actively respond to discomfort, by adjusting physical conditions (i.e. windows, blinds, heating, cooling, lighting controls, clothing), or by leaving the space where discomfort was experienced.

Occupants may take an active role in regulating comfort, including but not limited to activity, routine, clothing, social relationships, building technologies and interactions with building and systems (Shove, 2003a; Cole et al., 2008). They are shaped by individual attitudes and values, social and cultural norms, available technologies and the special arrangement of the home (Hinton, 2010). Some argue that we need to shift from strictly physiological and physical understandings of comfort that are concerned with establishing universal targets and environmental parameters, to adaptive strategies, socio-cultural and socio-technical understandings (Shove et al., 2008). From a socio-technical perspective, occupants co-evolve with technologies: assembling collections of technologies, arranging or using them in their own ways, and thus individualising these technological solutions through comfort practices (Gram-Hanssen, 2010). These individual practices are context-dependent and vary over time, influenced by building physics, physiology of the occupants and a range of climatic, social, economic and cultural factors (Nicol and Roaf, 2005). Understanding sociological and psychological aspects of occupants may play an important role in shifting comfort towards a more sustainable direction, and facilitating more effective practices.

2.2.5 Multidimensional Approaches

Comfort can be approached and understood in a set of inter-related systems including people and their immediate physical and social environment. These inter-related systems are mainly categorised into psychological, sociological, technical and socio-technical approaches to comfort (Table 2.1). "Different approaches attribute different kinds of agency to different kinds of social actors: in some, individuals are attributed the lion's share of agency; in others, technology drives energy consumption and comfort provision; and in others, social, cultural and socio-technical factors are considered to have agency on individual practices" (Hinton, 2010). These various approaches shape the way we understand comfort from different perspectives.

Table 2.1 Summary of the different approaches to comfort practices

	Function	Characteristics
Psychological approach	Based primarily on the occupants' attitudes and values	Focus on the mind of the individual; stress the significance of individual attitudes and values
Sociological approach	Based on social and cultural structure	Focus on the social body; stress the role of social structure
Technical	The role of technologies is	Focus on technologies within the

approach (comfort as attribute)	emphasised, while occupants are seen as passive recipients	home; stress technological optimal control in order to produce comfort
Socio-technical approach (comfort as achievement)	Both occupants and technologies are emphasised, and arranged in socio-technical assemblages; agency is distributed across different levels, from the socio-technical regime to the household, including practices themselves	Focus both on the individual body and its physiological responses, and on the ability of technologies to meet physiological needs; stress the significance of the ability for different configurations of technologies to produce environmental conditions under which the majority of participants report feeling comfortable

Social psychological approaches to understanding comfort have been long established, exploring individual attitudes and values and their links to human behaviour. In addition, a psychological approach focuses on individual characteristics, attitudes and values, whereas a sociological approach emphasises the role of social and cultural factors in shaping these attitudes and values. These two broad approaches have respectively been referred to as 'internalist' and 'externalist' (Jackson, 2005), or as 'attitude-behaviour connection models' and 'consumer-motivation theories' (Hargreaves et al., 2008). Where the former category focuses on individual agency, the latter puts the individual in a broader social and cultural context including social norms and social, economic and political factors. Jackson sees these two approaches as being in tension, where "in the first perspective, enlightened consumers are free to choose pro-environmental behaviours – assuming that they possess appropriate beliefs or attitudes; in the second, consumers may be 'locked in' to consumption choices by a variety of external conditions ranging from genetic conditioning to economic necessity, social expectation, accessibility constraints and the 'creeping evolution of social norms' " (Jackson, 2005).

However, social psychological approaches tend to focus only on people within their social and cultural contexts. These types of psychological, human-focused approaches to understanding comfort tend to ignore non-human or material agency – where technology is assumed to have little influence on individual behaviours – such that the effects of a non-human dimension (i.e. technologies and built environment) in shaping our actions or identities are ignored. Further, social psychological approaches reproduce divisions between people and the physical environment. This is not to argue that attitudes and beliefs, or mental models of behaviour and understanding of energy and the environment, are not involved in energy use and comfort practices: however, it is to argue that they may simply be one of a range of other influential factors which may be more or less dominant, where these factors can be considered to be networked together into a more-or-less self-reinforcing system (Hinton, 2010).

In contrast to sociological and psychological approaches, a technical approach to producing comfort has come to focus on applying different technical systems or artefacts to measure physiological responses to a set of environmental conditions. This approach has come to stress the importance of the application of 'optimised' environmental parameters and viewing occupants as passive recipients. It is referred to as 'technological determinism', which holds that technology not only develops outside of society, but can also influence it from the outside. It implies a greater role for material agency: individuals still have agency but this is mediated by structures external to the individual, which may include social and cultural norms, institutions, infrastructures and other material manifestations of social life (Hinton, 2010). For example, the built environment, comprising the electricity grid, heating infrastructure and drinking water systems, underpins and to some extent structures our everyday consumption (Spaargaren, 2000); as Ropke (2009) argues, "practices co-develop with changes in production technologies, supply chains, transport infrastructure, exchange institutions, retail systems".

Combining social psychological and technical approaches, a socio-technical approach recognises the roles of both technology and society, conceptualising the link between society and technology in subtly different ways. Comfort practices are thus structured by both socio-psychological understandings and technical systems, where all three – people, physical and social environment – co-evolve. A socio-technical view of comfort situates itself in a social and historical context (Shove, 2003a & b); shaped by collective conventions, co-evolving with technical regimes (Shove, 2003b; Guy, 2006); context-dependent (Hitchings, 2009); socially structured, with its meaning varying over time and space (Chappells and Shove, 2005; Shove, 2003a); culturally negotiable (Fountain et al., 1996; Cole et al., 2008; Shove, 2006); and having different approaches and understandings even within professional circles of architects, engineers, planners, developers, manufacturers and regulators (Shove, 2003a; Chappells and Shove, 2005). Skea (2009) argues that a holistic approach to understanding comfort would combine both sociological and psychological understandings of behaviour with technical ways in which comfort needs are structured; arguably both socio-psychological and technical approaches could be further enriched by considering the ways that socio-technical assemblages can frame comfort.

Comfort as viewed from a socio-technical perspective is uniquely distinguished from other approaches – such as those grounded in psychological or sociological understandings of behaviour – which sees agency distributed throughout socio-technical systems rather than in isolation and stresses the role of practices in constituting these systems. “The strength of this approach is its emphasis on the socially situated and networked nature of both technologies and practices, yet it could be criticised for paying relatively little attention to the potential role for individual psychological factors in practicing comfort, or socio-cultural structure, in contributing to this co-evolution of technologies and practices” (Hinton, 2010). In other words, this approach could be enhanced by considering individual motivations for undertaking particular actions and taking these as part of the socio-technical regime. The social and psychological approaches could also be expanded, by acknowledging the potential role of socio-technical systems in structuring individual attitudes and values and social norms. A more holistic approach to understanding comfort might consider practices, attitudes, values and norms as producing and produced by the socio-technical structure, where agency takes a networked form that recognises both technologies and practices.

2.2.6 Everyday Practices

The pursuit of comfort is a basic drive in human behaviour, which has had a profound environmental impact, relating directly or indirectly to increased household energy use. When considering the concept of ‘comfort’, an optimal and productive indoor environment is directed to stable and predictable comfort conditions, in the form of temperature, light, sound, and air quality to correspond to a standardised human ‘comfort zone’. Technological systems and material infrastructures are designed to provide such physical conditions in buildings; i.e. windows, radiators, thermostats, controls and insulation, each of which can have an impact on the level of energy use. As Shove (2003a) suggests, the technical standards and norms developed for building energy efficiency may have even fostered higher social norms of comfort, and thus higher energy consumption. Hence, the introduction of energy efficient technologies does not directly link to the seemingly promised reduction in domestic energy use or CO_2 emissions. To unfold and supplement the energy saving potential of these efficient buildings, user practices need to be taken into account (Gram-Hanssen, 2014).

A practice theory approach to indoor comfort and energy consumption has received burgeoning attention from around the world. Understanding and intervening in comfort through practice theory to drive the adoption of less energy intensive practices has been attempted in some research contributions. Shove proposes the idea of understanding comfort from people’s actions, as well as the relation between technologies, systems and appliances, and the co-evolution of routines, habits and practices (Shove, 2006). According to this view, comfort practices are both subject to and actively produce socio-technical systems, which highlight the social nature of practices and imply the best way to practise comfort (Hinton, 2010). In other words, comfort may best be achieved by adopting a ‘practice-oriented’ approach, which comprises an assemblage of human and non-human actors in routinised behaviours (Bulkeley and Gregson, 2009). Such an approach recognises agency in both occupant and practice itself, with implications for lower carbon interventions: “the more substantial challenge is to understand how consumers, users and practitioners are, in any event, actively involved in making and reproducing the systems and arrangements in question” (Shove and Walker, 2010). This approach puts emphasises on the interrelationships among technology, practice, and consumption, which has been adopted in a number of empirical studies relating to comfort and energy practices (Table 2.2).

Table 2.2 Synoptic overview of selected papers on comfort practices

Reference	Objective(s)	Methodology	Main finding(s)
Day and Hitchings 2009	To explore how older people in the UK manage their winter warmth and what contextual factors may influence this	21 households near Birmingham, UK; 2 semi-structured interviews in 2 winters and a photo diary for a few days during a cold period	Whilst older people continue to be relatively economical in their consumption overall, they do not tend to frame this in relation to the environment; they feel their heating behaviour is independent of a wider generational cohort of other 'older people'
Gram-Hanssen 2010	To develop practice theory within a social-technical approach	A questionnaire survey among 1000 households in Denmark; 30 households selected for measurements of indoor environment; 10 households selected for interviews	Practice theory can be used to explain differences within a socio-technical homogeneous group, including the four elements holding these practices together, which are the technologies, knowledge, habits, and meanings of residential heat comfort
Gram-Hanssen et al. 2012	To investigate to what extent individual air-to-air heat pumps in Danish dwellings and summerhouses actually deliver savings of energy	2793 households online survey in two Danish regions; 12 respondents selected for face-to-face interviews and technical inspections	On average there is no reduction in electricity consumption, as energy efficiency is counter balanced by increased comfort and changed heating practices

	use		
Hargreaves et al. 2013	To explore how UK householders interact with feedback on their domestic energy consumption in a field trial of real-time displays or smart energy monitors	275 households from across eastern England were recruited to trial three different smart energy monitors; 15 households sampled randomly in semi-structured interviews (6 face-to-face/ 9 telephone)	The level of engagement of households is a major factor in developing energy saving measures; The aesthetic appearance of the devices is essential; There are gender and age-specific styles of engagement with the devices and what they are communicating
Huebner et al. 2013	To gain a better understanding of human factors potentially related to energy consumption in domestic households, focusing on occupants' comfort	55 households in England; a home visit (by two authors), a tick-box survey, a semi-structured interview, monthly energy meter readings	Warmth was given most often as the meaning of comfort; Comfort practices were to a large extent defined as temperature-related actions with low energy use; a deficit in the quality and quantity of instruction on how to use the heating system was reported; being used to behaving in a certain way was seen as the most important barrier to behaviour change; Willingness to change behaviour was greatest in order to save money

Jaffari and Matthews 2009	To reconceptualise comfort that considers both environmental conditions and users' practices	Case study (4 families); long-term (3-year, during the winter months); ethnographic and physical monitoring (video, field notes, interviews, diaries, data loggers)	Comfort practices may extend more widely than interactions with technical systems: they can involve social interactions, acts of consumption and the use of different materials; it may be influenced by individual habit, family tradition, affordability, knowledge, aesthetic value, personality and temporal factors
Wilhite et al. 1996	To investigate the influence of cultural and economic factors on end use patterns for space heating, lighting and hot water use	18 households in Oslo, Norway and 16 households in Fukuoka, Japan; 1-1.5 hour in-depth open-ended interview	While energy intensive space heating and lighting habits have become an integral part of the presentation of the Norwegian home, Japanese space heat and light habits are more disciplined and less culturally significant; Bathing is extremely important to the Japanese lifestyle
Wright 2004	To gain greater understanding of older homeowners and private renters' experiences of heating their homes in winter and of the various	64 older homeowners and private renters (half of whom were classified as being in 'fuel poverty') living in the UK in 2003; a detailed questionnaire for	Reported experiences of thermal comfort varied with gender, health problems and age; this study illustrates the variability in how individuals even within the same home or the same social group practise comfort, and the influence

	issues of fuel poverty	factual information and an in-depth tape-recorded interview	of socio-technical assemblages on their practices

Practice theory is a fragmented body of theories that emphasises the importance of both body and things in understanding practice (Gram-Hanssen, 2010). It is based on the idea that “in the continual flow of activities it is possible to identify clusters or blocks of activities where coordination and interdependence make it meaningful for practitioners to conceive of them as entities” (Ropke, 2009). According to Schatzki (1996), practices are “coordinated entities that are temporally unfolded and constitute spatially dispersed nexuses of doings and sayings” (Gram-Hanssen, 2010). In other words, practice can be identified when a cluster of activities undertaken by an individual is recognisable and interdependent, which may be replicated across time and space. The application of practice theory approaches is identified as “the practice turn in contemporary theory” of social sciences, where the actions and expressions should be at the centre of analysing the social relations rather than focusing on signs and symbols (Schatzki et al., 2001). A practice theory approach considers how routines and technological structures contribute to the structure of practices, as well as how knowledge and attitudes hold practices together (Gram-Hanssen, 2010). Practice theory offers us a way of moving beyond the structure–actor dualism to explore how individual attitudes, social structures and technical systems help hold together what people do and say as practices (Ropke, 2009).

Practice forms the nexus where certain elements are holding the practice together (Gram-Hanssen, 2010). For example, Shove and Pantzar (2005) point out three elements holding practices together: material, meaning and competence; and Schatzki (1996) identifies three different elements: practical understandings, rules and teleoaffective structures. However, Gram-Hanssen (2010) criticises Shove and Pantzar for failing to distinguish between two main types of competence, ‘know-how’ or embodied habits, and rule-based or theoretical knowledge, and proposes a four-elements structure: embodied habits, knowledge, engagements and technologies. Gram-Hanssen argues that practice is an assemblage of interactions between people and things, along with what knowledge one has, and what engagements and meanings are associated with that knowledge (Gram-Hanssen, 2010). Here, practices involve interaction with material things or technologies, which has been emphasised by Warde (2005), Shove and Pantzar (2005), and Reckwitz (2002a & b); they are associated with particular attitudes or meanings for action; and they require certain forms of knowledge and habits in the individual performing the practice. "Habits and knowledge are partly embedded in individuals, but also partly embedded in the practices themselves since practices only exist through enactment, and since practices are social in that they are shared" (Ropke, 2009; Hinton, 2010).

2.3 Occupant Behaviour in Energy Retrofit

The significance of occupant behavioural impact in influencing the effectiveness of energy retrofit has been widely recognised (Steemers and Yun, 2009; Sunikka-Blank and Galvin, 2012; Ben and Steemers, 2014; Gram-Hanssen and Georg, 2018). The predicted energy savings associated with energy efficient technologies frequently exceed actual savings made due to behavioural factors (Stern, 1985; Gram-Hanssen et al., 2012; Sunikka-Blank and Galvin, 2012). These behavioural factors may be categorised into socio-economic variables (Steemers and Yun, 2009; Belaïd, 2016), lifestyle groups (Guerra-Santin and Itard, 2010) and socio-material configurations (Gram-Hanssen, 2010), in which social and material worlds are considered as inextricably entwined (Beaulieu et al., 2016). They may also be viewed from a practice perspective, within which what people do is structured and guided by a set of elements: embodied habits, institutionalised knowledge, engagements and technologies (Gram-Hanssen, 2014). While much effort has been devoted to making a house more energy efficient, the complexities of the occupants and their homemaking practices have often been ignored (Ellsworth-Krebs et al., 2015). Standardised behavioural assumptions are commonly used for home energy audits and policy interventions aiding in energy efficiency improvements (Kelly et al., 2012). Subsequently, the calculations based on these assumptions could undermine the validity of retrofit guidance (Ingle et al., 2014).

Domestic retrofit guidance in the UK has been primarily based on technically oriented energy audits. These audits typically focus on the physical characteristics of the dwellings, using building performance models with standardised behavioural assumptions to measure home energy efficiency (Kelly et al., 2012; Ellsworth-Krebs et al., 2015). Energy performance certificates (EPCs), for example, as a legal requirement for existing dwellings to be sold or rented since 2008, use the Reduced Standard Assessment Procedure (RdSAP) to evaluate home performance as well as to estimate and recommend effective improvements. Designed to assess the building rather than its occupants, RdSAP generates results that are independent of individual household behaviour. This means that the subsequent retrofit recommendations and estimates of the effectiveness of relevant measures are decoupled from any specific occupants. Similarly, as the main agency providing publicly accessible retrofit recommendations, Energy Saving Trust along with its web-tool Home Energy Check have also excluded variations of energy saving potential resulting from different household behaviours. Consequently, retrofitted homes might result in significantly less energy savings than expected, hindering the process of effectively achieving carbon emission reduction and reducing confidence in investment decision-making. A study using dynamic building simulation showed that occupants' heating behaviour significantly influenced the energy-saving potential of retrofit measures: active heating users could achieve almost twice as much energy saving as passive heating users (Wei et al., 2017). Dodoo et al. (2017) found that indoor air temperature influenced performance of energy efficiency measures significantly. Therefore, addressing behavioural variations in retrofits is crucial for achieving the anticipated savings.

2.3.1 Behavioural Modelling

Occupant behaviour can vary building energy performance by a factor of two or more (Steemers and Yun, 2009; Gram-Hanssen, 2014). Better incorporation of behaviours in energy performance prediction can thus improve the reliability of modelling estimation and subsequent retrofit recommendations. However, energy consumption is complex. Employing standard and simplistic behavioural profiles in energy modelling leads to a significant discrepancy between actual usage and prediction (Menezes et al., 2012). For energy demand reduction, an approach incorporating the complexity of behaviour is needed that captures the key determinants of energy performance to allow better evaluation of energy saving policy programmes and retrofit options.

Collecting and employing an exhaustive dataset on occupant behaviour for each household in home energy audits is likely to be unrealistic. Researchers have developed various behavioural models typically utilising time use data and stochastic processes for more accurate estimation of domestic energy use (Virote and Neves-Silva, 2012; Widén and Wäckelgård, 2010; Richardson et al., 2010; Tanimoto et al., 2008). Some behavioural models identify patterns of behaviour using statistical analysis procedures, data mining and machine learning techniques (van Raaij and Verhallen, 1983a & b; Jones et al., 2017). For example, behavioural models using statistical algorithms predict the probability of an action or event (e.g. opening a window) at certain conditions. Such models have usually been formulated concerning one type of behaviour at a time, based on field investigations that collect large amounts of data to establish relationships between environmental factors and targeted operations, and can be integrated in simulation software for more accurate calculation. However, these developed models are insufficient for general applications, considering the requirement for the numerous building typologies, cultures, climates, and so on (Yan et al., 2015). Furthermore, despite that platform exists to integrate occupant models (Bourgeois et al., 2006) into one software package, there is a lack of complete and interlinked set of models considering all aspects of occupant behaviour (Fabi et al., 2011).

Meanwhile, the representation of occupant behaviour in building simulation tools for energy performance modelling often use a simplified and deterministic approach, such as using static schedules which are fully predictable and repeatable. Moreover, many of the behavioural profiles are translated into their possible effects as input into the simulation tools, such as the control of windows being converted to air change rate per hour. In addition, a developed behavioural model may be incompatible with a simulation tool if the model inputs are not readily available (Yan et al., 2015). Nevertheless, the ultimate goal is for simulation tools and models to provide a reasonable prediction of occupants in most situations, depending on the problem that is being addressed. In other words, the robustness of the model comes with a balance between practicality and accuracy. Currently, many energy simulation tools exist with different levels of complexity, among which Energy Plus, ESP-r, IDA ICE, IES-VE and TRNSYS are the most complex and complete tools (Sousa, 2012; Jarić et al., 2013).

When developing behavioural models for building performance simulation, levels of complexity should be based on the demand of application levels (Yan et al., 2015). The parameters involved should also have reasonable justifications and explanations rather than according to the mathematical form of data fitness alone. Another challenge is the variety of occupants. Yan et al. (2015) suggested a "typical occupants" approach as a probable path forward such that it serves industry.

Current behavioural modelling in building simulations addresses behavioural complexity but excludes occupants' socio-demographics and household characteristics which are crucial for identifying specific target groups (Andersen et al., 2016; Gaetani et al., 2016). An alternative is to create an archetype for each significant class of household based on statistical analysis, and then examine different ways of tackling energy efficiency according to the characteristics for that archetype. In this context, an archetype is defined as a typical example of households sharing similar behavioural patterns and dwelling physical characteristics. If the archetypes are carefully selected, this procedure enables a tailored evaluation of the different household types along with their different energy consumption patterns and potentially different responses to energy efficiency interventions.

2.3.2 Archetypes and Clustering

Archetypes are particularly helpful in exploring policy opportunities geared towards different household groups, because they have the potential to support analyses of energy usage trends and patterns at more disaggregate levels (Hughes and Moreno, 2013). Moreover, archetypes can be used to make future projections by exploring changes in household behavioural patterns and energy retrofit options, while developing priorities for research and development. They can also be used to predict various possible scenarios and provide the basis for strategic planning carried out by governments and relevant stakeholders (Famuyibo et al., 2012).

The archetype approach has been adopted by a number of researchers on domestic retrofit and energy performance. The majority of them employed building archetypes defined only by dwelling physical characteristics in combination with appropriate proportions to represent the housing stock (Farahbakhsh et al., 1998; Ballarini et al., 2011; Famuyibo et al., 2012; Kavgic et al., 2013; Cerezo et al., 2015; Ghiassi et al., 2015; Sokol et al., 2017). These building archetypes were categorised based on various variables determined distinctively in each study, subjected to a selection of key variables. For example, variations in space heating were the primary concern for identifying archetypes in the work by Kavgic et al. (2013), whereas the TABULA project had fixed three independent variables: location, age and geometry (Ballarini et al., 2011). The primary aim of these studies using archetypes was to develop building energy models for testing retrofit strategies. However, due to a lack of association between these building archetypes and occupant behaviour or household characteristics, large discrepancy may exist as to the actual energy consumption and subsequent retrofit performance estimations related to the archetypes identified.

In recent decades, an increasing number of studies have been conducted with the aim of determining household archetypes and segmentation, behavioural patterns, occupancy profiles in relation to energy consumption as well as household characteristics (Raaij and Verhallen. 1983b; Guerra-Santin, 2011; Sütterlin et al., 2011; Zhang et al., 2012; Hughes and Moreno, 2013; Poortinga and Darnton, 2016). Household archetypes can be defined by household characteristics, lifestyle and behavioural patterns, attitudinal variables as well as by physical characteristics of the dwellings. Through differentiating occupants or energy consumers, polices can be devised in a targeted manner to achieve more effective outcomes. For example, in what is perhaps the most inclusive development of residential energy consumer archetypes, Zhang et al. (2012) proposed a three-dimensional conceptual model and identified eight archetypes: 1) pioneer greens; 2) follower greens; 3) concerned greens; 4) home-stayers; 5) unconscientious wasters; 6) regular wasters; 7) daytime wasters; 8) disengaged wasters. Energy policy and interventions were designed for each of these archetypes that integrated the factors extensively studied in previous research into UK domestic energy use. However, while this study has informed policy regarding the need for a tailored and multidimensional approach, there is little information about the socio-demographic characteristics of these archetypes, making it difficult to determine their applicability in practice and thus the way to employ them for energy demand reduction.

Meanwhile, there are studies aiming to segment households through distinguishing clusters of behavioural patterns statistically and derive subsequent different energy conservation strategies. For example, Raaij and Verhallen (1983b) identified five behavioural patterns and found that these behavioural patterns (clusters) corresponded with considerable variations in energy use, and each cluster associated with different socio-demographic and attitudinal characteristics. Similarly, Guerra-Santin (2011) identified five behavioural patterns along with certain distinct household and dwelling characteristics connected to each pattern. Previous studies have already revealed different statistical approaches to clustering energy consumers and making household archetypes for targeting energy efficiency improvements. Table 2.3 presents key references on identifying different energy consumer segments, including a brief outline of sample, method and outcome. These studies analysed the interdependencies between occupant behaviour, attitude and energy consumption, while identifying certain segments or archetypes based on different methods. Nevertheless, as every author analysed data collected with a different set of pre-determined parameters and each archetype was derived with an element of subjective interpretation, the resulting clusters differ as well.

Table 2.3 Summary of existing research on household clustering and segmentation

Author(s)	Sample size	Date	Location	Data analysis method	User groups
van Raaij and Verhallen (1983)	145	Nov 1976 – Nov 1977	Vlaardingen, the Netherlands	Principal component analysis; pattern analysis; discriminant analysis	Conservers; spenders; cool; warm; average
Defra (2008)	378	2007	England	Cluster analysis	Positive greens; waste watchers; concerned

					consumers; sideline supporters; cautious participants; stalled starters; honestly disengaged
Guerra-Santin (2011)	313	Autumn 2008	Leidsche Rijn in Utrecht and Wateringse Veld in The Hague, the Netherlands	Correlation analysis; strings classification; exploratory factor analysis;	Spenders; affluent-cool; conscious–warm; comfort; convenience
Sütterlin et al. (2011)	1292	Nov 2009 – Jan 2010	Switzerland	Cluster analysis; Correlation analysis	Idealistic energy saver; selfless inconsequent energy saver; thrifty energy saver; materialistic energy consumer; convenience-oriented indifferent energy consumer; problem-aware well-being-oriented energy consumer

Hughes and Moreno (2013)	250	2010 – 2011	England	Factor analysis; cluster analysis	Profligate potential; thrifty values; lavish lifestyles; modern living; practical considerations; off-peak users; peak-time users
Poortinga and Darnton (2016)	1538	May – Jul 2011	Wales	Cluster analysis	Enthusiasts; pragmatists; aspirers; community focused; commentators; self-reliant

2.4 Research Rationale

The interplay among retrofit, occupant behaviour and comfort has received extensive interest in the study of sustainable buildings. From the technical science perspective, the approaches often lie in making energy models which can be used either for prediction or for optimizing technologies in the design phase (Brohus et al., 2009; Page et al., 2008; Rijal et al., 2008). For example, a set of standard comfort conditions have been designed to match physiological needs, such as ‘thermal, air quality, visual, acoustic, ergonomic, and psychological comfort’ (ASHRAE, 2017), resulting in provision and maintenance of a fixed set of physical conditions (Cole et al., 2008) but neglecting the social and behavioural dimensions of comfort. From the social science perspective, the primary focus is placed upon describing and understanding households’ energy consumption related to comfort (Shove et al., 2008), using segmentation and lifestyle approaches, socio-economic understandings and practice theory (Warde, 2005; Gram-Hanssen, 2010; Strengers, 2011; Hargreaves, 2011). For example, practice theory focuses on the collective and structural elements of what people actually do and say, including technologies, competences and meanings

(Shove, 2003a), and have primarily been qualitative studies. So far, the technical scientific approach and the social science approach have been rather separated from each other, lacking the combination of both qualitative and quantitative analyses.

This research aims to gauge the gap between the technical scientific approach of modelling and predicting and the social science approach of describing and understanding occupants in terms of their comfort and energy practices. The idea is to bring these two approaches together, and to broaden the analysis and include qualitative as well as quantitative techniques. It will utilise research methods for modelling and predicting occupants' energy consumption as well as understanding occupants' comfort needs. Furthermore, the ambition of the research is to use the insights of occupant comfort and energy practices to develop effective retrofit strategies that would increase energy savings without compromising occupant comfort. The results should improve communication in both development and operation of domestic retrofit, and help develop more user-adapted buildings.

Studies have illustrated variability in practices: variability in individuals' socio-technical assemblages, the ways households regulate their comfort, and individuals' comfort experiences with widely varying environmental conditions. Whilst comfort has been studied from various angles and in various contexts, little attention has as yet been paid to the understanding of variability in energy consumption using practice theory. In addition, few of these studies have adopted an explicitly practice-theory inspired approach despite focusing on and talking about practices (Gram-Hanssen, 2010). Whilst comfort is well theorised in the literature, there is a relative paucity of comfort studies that have contributed to empirical explorations of how practices influence household energy use at home.

In addition, while existing studies have identified building archetypes, consumer typologies and behavioural patterns, there is a current lack of research on evaluating how different retrofit strategies respond to various segments, which have identifiable characteristics so that policies and programmes may be devised towards targeted households. Some studies have shown the extent to which occupant behaviour is connected with certain types of socio-technical and psychological characteristics (Sütterlin et al., 2011; Zhang et al., 2012; Poortinga and Darnton, 2016). There has, however, been little work done to develop archetypes that statistically combine occupant behaviour, comfort, energy use, household and dwelling characteristics. The determination of household archetypes with detailed profiles and behavioural patterns would lead to more accurate energy saving estimations from retrofit and, at the same time, help organisations in the energy industry to make better predictions and decisions.

Finally, research into the behavioural impact on building energy performance has mostly focused on the building design and operation stages. The influence of occupant behaviour in the building retrofit stage needs to be further explored. So far, only a few studies have quantified the role of behaviour on the effectiveness of energy retrofit measures. These studies found that the effectiveness of energy efficiency measures varied depending on the occupancy pattern of the household (Marshall et al., 2016), occupant heating behaviour (Wei et al., 2017), as well as site-specific parameters such as the indoor air temperature and internal heat gains from building occupants and electrical appliances (Dodoo et al., 2017). However, none of them investigated how the optimal selection of energy efficiency measures would vary with different households. Little is known about the behavioural impact on the optimal ranking of retrofit measures in terms of their energy saving potential. In order to fill this gap, this research further examines the performances of retrofit measures, especially with regard to the optimum retrofit options, among different household archetypes. The result will inform a prioritised list of retrofit options tailored to different types of households. The outcome will support decision making in energy policies and programmes.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the overarching research philosophy, and its design and methods. The research addresses the gap between a social science approach of understanding occupants and a technical scientific approach of modelling building energy performance to improve energy saving predictions. Its underlying assumptions stem from a socio-technical perspective. Thus the research adopts a mixed-method approach to assess both household perceptions and retrofit technologies. It combines both qualitative and quantitative techniques, using an exploratory sequential design to investigate the research problem. The data collection and analysis methods are detailed below, followed by a brief section on research ethics.

3.2 Research Philosophy

This thesis adopts a post-positivist paradigm as its research philosophy. Essentially, post-positivists believe that there is an objective world, but knowledge of it is bound by human and social constructions (Popper, 1959; Kuhn, 1962; Popper, 1963; Hacking, 1983; Cartwright, 1989; Crotty, 1998). Within this paradigm, the research design is guided by critical realist ontology, where reality is both intransitive and stratified (Bhaskar, 2008; Archer et al., 1998). Meanwhile, the interpretation of the results is based on constructivist epistemology, recognising the role of human perception and social experience in constructing knowledge (Piaget, 1977).

The post-positivist paradigm advocates methodological pluralism, in which the method for a particular study is based on the research question being addressed (Wildemuth, 1993; Krauss, 2005). Consequently, this research chooses a sequential exploratory mixed-method design to uncover the most appropriate hypothesis and then test it through confirmatory processes (Creswell, 2009). It applies an interpretive approach to exploring occupant comfort practices conducted prior to a positivist approach to developing household archetypes and retrofit strategies. The interpretive approach aims to understand the social world from the actors' viewpoints, identifying important variables and generating a hypothesis. From this, the positivist approach discerns the statistical regularities of behaviour and tests the approach being developed (Wildemuth, 1993).

3.3 Research Design

Based on a post-positivist paradigm, the research was carried out using a sequential mixed-methods approach (Figure 3.1). Initially, the study explored occupants' perceptions and experiences related to social practices of comfort. Based on the insights from an understanding of occupants, the research then used confirmatory studies to identify household types and evaluate retrofit strategies with quantitative methods.

The research procedure was structured into three consecutive phases (Figure 3.2). Phase I explored household comfort practices, which provided the basis for Phases II and III. Phase II consisted of the quantitative study of household archetypes and behavioural patterns for energy retrofit strategies. Subsequently, Phase III focused on how the household archetypes affected the effectiveness and optimal rankings of retrofit technologies. The specific data collection and analysis methods of all three phases are further described in the next section.

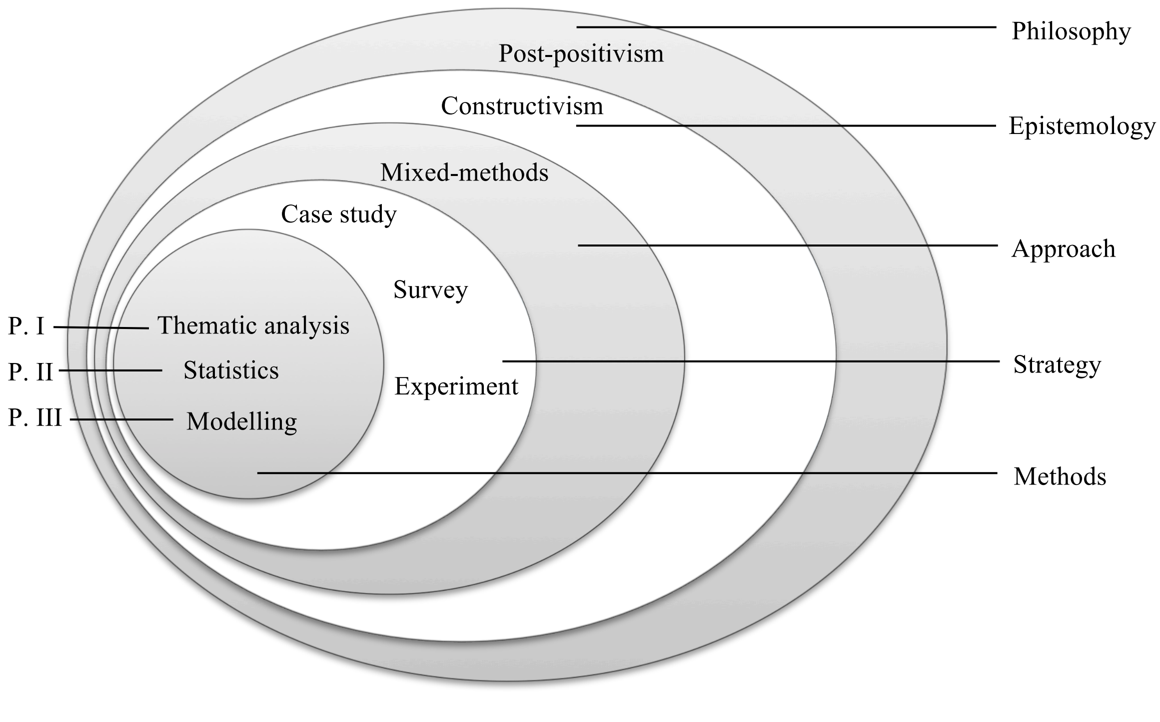


Figure 3.1 Research methodology outline (Adapted from: Saunders et al., 2012)

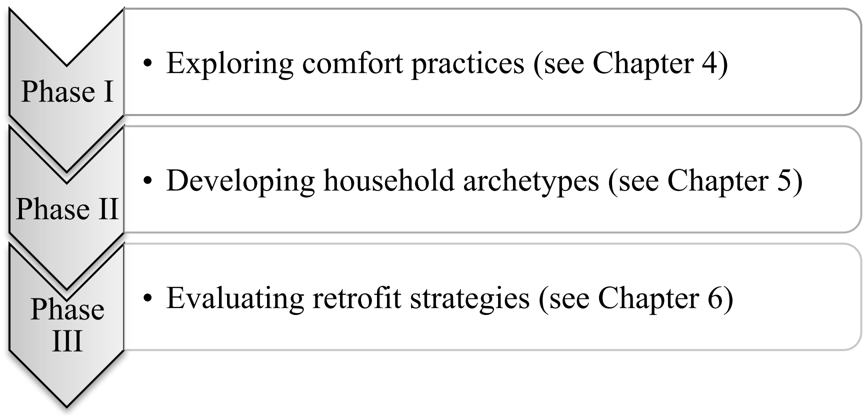


Figure 3.2 Sequential phases of the research

3.4 Data Collection and Analysis Methods

3.4.1 Phase I - Exploring Comfort Practices

The aim of Phase I was to thoroughly explore the underlying social practices relating to occupant comfort, capturing the individuals' experiences and perceptions using a mixed-method data collection process. This study began with understanding users according to their comfort practices, energy-related behaviour and daily activities. It focused on actual practices in the everyday lives of the households, using in-depth case studies of households living in Cambridge, UK. It employed triangulation processes to collect a combination of qualitative and quantitative data. Here triangulation was used to promote the validity of data findings and support a better exploration and understanding (Maggs-Rapport, 2000). The study then used template analysis to interrogate the data, with the pre-selected codes informed by social practice theory.

3.4.1.1 Data Collection

The study used a primarily qualitative approach to explore household comfort practices in Cambridge, UK. Fourteen households participated in this study (Table 3.1) and they were interviewed and monitored between January and March 2014. The data collection process included a semi-structured interview, questionnaire survey, diary-log record, data logger monitoring, observation, and photo record (see Appendix A). The interviews were all carried out in the participants' homes, and each lasting about 2 to 3 hours. Interviewing at participants' homes provided the opportunity to enhance the richness of the data collected, as the space was integral to the study and could add to the rapport between participant and researcher (Elwood and Martin, 2000; Herzog, 2005).

Interviewees were briefed about the research topic before the interviews. A set of predesigned questions was used to guide the interviews, alongside spontaneous queries allowing new ideas for exploration during the interview. The questions were designed to obtain information on occupants' social practices, such as their perceptions, activities, living environment and household characteristics. The surveys were carried out along with the interviews, after which the data loggers were set up inside each participant's home. The number of data loggers was determined according to the number of main rooms occupied by each household. During the one-week data-logger monitoring period, each participant filled in the diary-log.

The selection of the sample was not aiming for representativeness, but to allow for a richer and deeper description and breadth of analysis with respect to occupant comfort practices. It was an exploratory study of household practices for structuring the constituents of occupant comfort in relation to energy demand. The purpose is to understand people's perceptions, opinions and beliefs, as well as the way they interacted with their environments. Unlike quantitative research, the purpose is not to generalize the results to the population of interest, but it is to be able to ensure a level of engagement to enable detailed information to be obtained. Some of this information is qualitative, and some is used for quantitative analysis. Qualitative analysis aims to gain an understanding of underlying reasons, opinions, and motivations. It provides insights into the problem or helps to develop ideas or hypotheses for potential quantitative research. Meanwhile, quantitative analysis offers a structured way of collecting and analysing data obtained from different sources. Quantitative research involves the use of computational, statistical, and mathematical tools to derive results.

Within the dataset, there were several dimensions of variability among the participants, such as household composition, the built form and dwelling type, as well as variations in terms of heating systems and type of energy bill. The participants selected were known previously to the researcher, which may have led to a better participant response. Although this may have produced a greater willingness for the participants to engage in the interviews, this does not necessarily influence the results obtained from the interviews. Since the participants selected were existing contacts through private communication, such personal connection might have triggered higher likelihood of participation and reduced variance of socio-demographic characteristics. However, the bias of such selection does not influence the research outcome other than participants' willingness to share information; triangulation was involved for determining the credibility of reported data. Therefore, the interviews and their implementation, as well as the technical aspects under investigation are assumed to remain unbiased.

Table 3.1 Participants' profiles

Case	Age	Occupation	Household type	Ownership	Energy bill	Dwelling type
A	32	Student	Couple	Private rented	Electricity - pay by consumption, gas and hot water - included in rental	Maisonette
B	31	Student	Couple	Private rented	Fixed bill payment to landlords	Flat (in listed semi-detached house)
C	63	Academic	Family	Privately owned	Pay by consumption	Terraced house
D	30	Student	Single	Private rented	Included in rental	Flat (in semi-detached house)
E	28	Student	Single	Private rented	Pay by consumption	Bedsit (in terraced house)
F	32	Academic	Couple	Private rented	Standard tariff	Flat (in townhouse)
G	30	Academic	Single	Private rented	Included in rental	Flat (in semi-detached house)
H	33	Student	Single	Private rented	Included in rental	En-suite room (in multi-level block)
I	24	Student	Single	Private rented	Included in rental	Flat (in multi-level block)
J	41	Academic	Family	Private rented	Electricity - pay by consumption; Heating, College CHP - included in rental.	Garden apartment
K	23	Student	Single	Private	Included in rental	En-suite room

				rented		(in multi-level block)
L	28	Student	Couple	Private rented	Pay by consumption	Flat (in multi-level block)
M	26	Student	Single	Private rented	Included in rental	En-suite room (in multi-level block)
N	26	Student	Single	Private rented	Included in rental	Bedsit (in semi-detached house)

3.4.1.2 Data Analysis

This section presents a theoretical framework from practice theory for template analysis of household comfort practices. Template analysis is a type of thematic analysis which employs hierarchical coding to structure qualitative data with a degree of flexibility for adaptation towards a particular study (Brooks et al., 2015). Several case studies were selected to exemplify on a micro-level what occupants do on a daily basis and their engagement with their living environment. Moreover, a typical day was chosen from the monitoring period from each case study to show occupants' daily routines and activities, with temperature data shown in an hourly sequence. Overall, the data was interrogated and analysed using pre-selected codes according to the chosen themes.

Social practice theories provided a useful set of concepts to understand and analyse comfort and consumption (Bourdieu, 1977; Giddens, 1984; Reckwitz, 2002a, 2002b; Schatzki, 2002; Shove and Pantzar, 2005, 2007; Warde, 2005; Gram-Hanssen, 2010; Hargreaves, 2011; Shove et al., 2012). According to Sherry Ortner (2006), practice theory seeks to explain the relationship between human action and the system. Bourdieu (1984) explored the interplay between field, capital and habitus, with the three elements holding practice together. Giddens (1984) suggested that social relations are structured across space and time due to 'structuration' where 'principles of order could both produce and be reproduced at the level of practice itself'. Schatzki (1996, 2005) defined practices as 'open-ended spatial-temporal manifolds of actions' and 'sets of hierarchally organized doings/sayings, tasks and projects', consisting of four main elements: practical understanding, rules, teleoaffective structure and general understanding. Reckwitz (2002) argued that a practice is a routinised type of behaviour, configured or shaped by many elements including 'forms of bodily activities, forms of mental activities, things and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge'. Shove and Pantzar's (2005) proposed that 'practices involve active integration of materials, meanings and forms of competence'. Gram-Hanssen (2010) showed 'how technological configurations, everyday life routines, knowledge, and motivation constitute the practice and also structure the possibilities for change'.

Drawing on the above-mentioned social practice theorists and researchers, their findings informed a conceptual framework for understanding and analysing households' comfort and consumption, such as heating, ventilation, cooking, bathing, laundering, dishwashing and house cleaning. In this research, four intersecting theoretical concepts have been adopted based on existing understandings of practices and their suitability for empirical analysis. The four elements that constitute a practice are described below, including meaning, composition, task and material. They were adapted from Shove et al.'s (2012) three-element Social Practice Framework (meanings, materials and competences) to further distinguish between implicit social rules (composition) and various forms of activities (task) within the element of competences.

The element of 'meaning' include symbolic meanings, ideas and aspirations, representing the reasons and motivations for doing certain things (Shove et al., 2012). Often referred to as goal, objective, aim, purpose, intention or desired result, 'meaning' informs the mindset behind actions. Practical understanding and 'meaning' are distinguished here to highlight the differences between know-how and motivation (Shove, 2003a; Wilhite et al., 1996). According to Schatzki (2002), 'what makes sense to someone to do is not the same as what someone thinks is appropriate, right or correct'. While 'meaning' conveys a sense of motivation about certain actions, it mainly engages practices through normative attitudes or views. It embodies an interpretation of the mental, which represents the psychological context of behaviour. It is through 'meaning', or understanding of psychological conditions for specific meanings that everyday practice can be interpreted or engaged.

'Task' or activities encompass both everyday action as well as 'routinised bodily and mental activities' (Reckwitz, 2002). It can also be recognised as embodied habits that make sense for a person to carry out at any moment, largely informed by what they have always done (Schatzki, 2002). Practice theory scholars refer to task in different ways, such as routinised activities (Reckwitz, 2002), habitus (Bourdieu, 2005), aggregated doings and sayings (Schatzki, 2002), everyday life routines and embodied habits (Gram-Hanssen, 2010). Bourdieu and Giddens refer to such activities as a deeply embedded layer of habits that is replicated in nearly everything we do. These activities are supported by practical intelligibility (Schatzki, 1996), know-how (Shove et al., 2012), as well as unconscious and submersed nature of practical understanding (Bourdieu, 2005; Giddens, 1984).

Composition or social rules represent the social norms, regulations, or negotiations over certain practices carried out by individual agencies. For Schatzki (2005), 'rules' refer to 'explicit formulations, principles, precepts, and instructions that enjoin, direct or remonstrate people to perform specific actions'. Bourdieu (1977) refer to such composition as 'field': 'a structured social space with its own rules, schemes of domination, legitimate opinions'. Rules also perform as authorities, restrictions, standards and recommendations pronounced by governing bodies, which are not necessarily subject to enforcement, but can hold the same status as many laws, becoming the source of social censure and of a regime of appropriate and inappropriate practices (Strengers, 2010). More broadly speaking, normativity is embedded in the social norms and general rules, depending on the composition or social structure. While regulatory rules are often explicitly produced or stated by influential institutional or commercial bodies, they are subject to extensive public debate and manipulation with reference to existing 'normal' practice (Strengers, 2010). Similarly, implicit rules directing what constitute as appropriate or inappropriate behaviours, are also shaped by cultures and evolve over time. In addition to the above-mentioned rules, there is a further aspect of composition including influences and compromises that arise from the interactions among various actors (Watson, 2016).

The element of 'material' refers to things, infrastructures, technologies, tangible physical entities and the stuff of which objects are made (Shove et al., 2012). It often shapes the practice itself instead of being a passive bystander; all practices undertaken in the household require certain forms of physical conditions and technologies. This process can be seen as 'scripting' (Akrich, 1992), whereby the physical component prescribes or directs certain practices and outcomes. As Schatzki (2010) claimed, 'practices are carried on amid and determinative of, while also dependent on and altered by, material arrangements'. Material infrastructure influences people's experiences and sensory relationship with reality, and in doing so it alters our perceptions and reactions (Verbeek, 2006). According to Jelsma (2006), morality and immorality can be scripted into material infrastructure, which can lead to more or less consumption than needed. These problems could be avoided if we recognise that material infrastructure can guide 'patterns of unconscious actions… acting like beacons and signs' (Jelsma, 2006). However, physical conditions can be extremely difficult to change. Many are long lasting and path dependent, 'locking in' particular practices that may outlive their original rationale (Arthur, 1989). As many are persistent and difficult to change, they are often overlain with other physical structures or rules in an attempt to reconfigure the practices they are implicated in (Strengers, 2010).

3.4.2 Phase II - Developing Household Archetypes

The second phase of the research was to further identify household archetypes and behaviour patterns using a large quantitative survey and then statistical analyses. This was built on the outcome of the previous phase, which provided the context for formulating the hypothesis and developing the survey questionnaire. This (Appendix B) was designed so as to cover the aspects of energy use, comfort, behaviour and household characteristics. The questionnaire was paired with data on building characteristics obtained from the Domestic Energy Performance Certificate Register (DCLG, 2014). As energy behaviour is contingent with other behaviour associated with household lifestyle (Guerra-Santin and Itard, 2010) and space heating has the greatest impact on energy use (Ben and Steemers, 2014), behaviour in this research was defined as the use of space, daily activities and the use of space heating. These behaviours were surveyed in a measurement of hours on a weekly basis, such as the total hours the occupant spent in the bedroom in a typical week. Household characteristics included socio-demographic variables shown to influence energy consumption in previous studies (Steemers and Yun, 2009; Guerra-Santin and Itard, 2010; Chen et al., 2013): age; tenure type; household size; household composition; work-status; occupation; education; and household income. Appendix C shows the survey data report on the characteristics of the dataset.

3.4.2.1 Data Collection

The survey was carried out during spring 2015 in Cambridge, UK. Based on the availability of Energy Performance Certificates (EPC) from the EPC Register, households were selected using postcodes to ensure that data on the dwellings' physical characteristics could be collected. A total of 400 postcodes were chosen with the intention to have surveyed households equally distributed among five Cambridge postcode districts from CB1 to CB5. A questionnaire containing 24 question sections was created online using Qualtrics Survey Software and printed out for face-to-face and postal surveys. A link to the online survey was offered as a complementary option for participants filling it in. A total of 78 households participated in the surveys, including 55 usable cases (response rate 28%) from face-to-face surveys and 23 usable cases (response rate 12%) from postal surveys. The number of respondents was constrained due to the limited number of households with an EPC available, the non-presence of people at home during the face-to-face survey as well as the length and detail of the questionnaire. The sample size was also in part determined by the timeframe and purpose of this research. Nevertheless, for a 'proof-of-concept' study, the sample size is sufficient to provide a confidence level of 90% and a margin of error within 10%. A calculation using SurveyMonkey (SurveyMonkey, 2019) or Qualtrics sample-size calculator (Qualtrics, 2018) based on population size of 46,714 as the Cambridge household number (Cambridge City Council, 2018) gives support to the sufficiency of the sample size. As Cambridge is a more affluent city compared to other areas within the UK, households with low income and low levels of education were underrepresented.

3.4.2.2 Data Analysis

Following data collection, the analysis mainly used the Statistical Package for the Social Sciences (SPSS) to identify the behavioural factors and to further develop household archetypes. SPSS was chosen for its sufficient capability to perform the following statistical analyses contributing to the objective of this phase of the research. These analyses were carried out in a sequential manner, including factor analysis, statistical pattern analysis and correlation analysis (Figure 3.3).

Initially, an analysis of the factors underlying behaviour was carried out using factor analysis with the principal component method (Figure 3.3, a). The principal component analysis (PCA) is a factor extraction method that transforms a number of variables into a smaller set of uncorrelated variables, called principal components. The first principal component accounts for maximum variance, and each succeeding component accounts for progressively smaller portions of the variance. PCA is employed to obtain the initial factor solution through dimensionality reduction (Wold, 1987). Here such analysis is acceptable for a relatively small sample, as long as communalities are high, the number of expected factors is relatively small and any model error is low (Preacher and MacCallum, 2002).

Subsequently, behavioural patterns were defined using statistical pattern analysis by dichotomising the factor scores of each case derived from the previous step and categorising the cases accordingly (Figure 3.3, b). This method was performed in the form of a data matrix, classifying data into categories and combining these categories into a set of patterns. These patterns were defined based on strings classification and interpretation of the common characteristics of the clustered cases. Raaij and Verhallen (1983) and Guerra-Santin (2011) have also used this method to determine residential energy behavioural patterns.

Finally, the household archetypes were developed based on relationships between the behavioural factors and the following: household characteristics; energy use; comfort; and dwelling characteristics (Figure 3.3, c). These relationships were explored using the Spearman's rank-order correlation coefficient (ρ), which is a nonparametric measure of rank correlation. Spearman's correlation assesses the strength and direction of relationship between two variables through a monotonic function. The variables can be measured on an ordinal, interval or ratio scale. The value of the coefficient (ρ) is a number between -1 and 1 that determines if the two tested variables are related, with 1 meaning perfect positive correlation, -1 meaning perfect negative correlation and 0 showing complete independence. Typically, a low ρ-value of either 0.01 or 0.05 is used to reject the null hypothesis and suggest that a relationship exists.

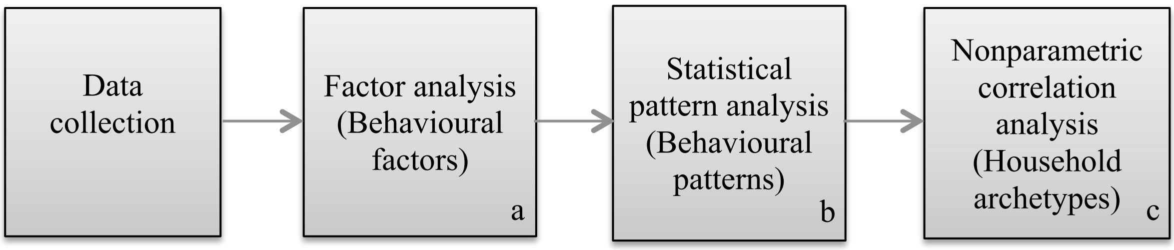


Figure 3.3 Methodology. **a** Analysis of the factors underlying behaviour using factor analysis with the principal component method. **b** Defining behavioural patterns using statistical pattern analysis by dichotomising the factor scores of each case derived from the previous step and subsequently categorising the cases accordingly. **c** Determining household archetypes based on the relationships between the behavioural factors and the following: household characteristics, energy use, comfort, dwelling characteristics

3.4.3 Phase III - Evaluating Retrofit Strategies

The last phase focused on testing the effectiveness and optimal rankings of energy retrofit solutions for the distinct household archetypes developed in the previous phase. The objective of this phase was to demonstrate the hypothesis that when retrofit strategies are tailored to household archetypes, the results improve energy savings while maintaining occupant comfort. This study utilised a given sample and case study dwelling in the analysis to exemplify the importance of incorporating household archetypes in developing retrofit strategies. It also illustrated the impact of using a modelling approach incorporating household archetypes at urban level, benchmarked against a standard procedure used by EPCs.

3.4.3.1 Data collection

The data for this final phase came from two major sources: the survey from the previous phase as well as Integrated Environmental Solutions - Virtual Environment (IES-VE) default data and published data such as ASHRAE and CIBSE Guides. Appendix D shows sample input data. A set of the most commonly used energy efficiency measures was identified and incorporated into the building energy modelling. The values of the dwelling parameters before and after the inclusion of these retrofit measures were derived from typical values collected from academic and industrial literature. The inclusion of each measure in the IES-VE building model was achieved by translating the physical aspects of each measure into model inputs. For example, the parameter for external wall insulation was the U-value of the external wall. Parameters with a broad range of values were modelled in order to demonstrate the sensitivity of the dwelling energy performance to each energy efficiency measure.

Furthermore, the cost of each measure was based on current market prices and the most economical options. Finally, the evaluation of the impact of household archetype at urban level used Cambridge as the case study, while the population proportion of each archetype was assumed on the basis of the Phase II survey.

3.4.3.2 Data analysis

Dynamic building simulation modelling was employed to assess the performance of individual retrofit measures across various household archetypes. The modelling processes were carried out using IES-VE, an internationally recognised 3D building performance analysis software, which allows for retrofit measures and occupant behaviour to be modelled at a highly detailed level. IES-VE was ranked as the top '*Architect Friendly*' tool for building performance simulation (Attia et al., 2009). It is particularly useful for representing HVAC controls and also has a sufficient level of accuracy.

The modelling procedure entailed several sequential steps. First, household archetypes were specified together with a range of retrofit measures to be tested. Then a base case was built for testing retrofit options using the archetypes independent of dwelling change, in order to single out the influence of occupant behaviour. Subsequently, all retrofit measures were simulated one at a time across the archetypes with respective dwelling types in order for their performances to be compared.

Five household archetypes were identified: active spender; conscious occupier; average user; conserver; and inactive user. These were derived from the Phase II study carried out in 2015 (Ben and Steemers, 2017), in which a survey and statistical analyses were used to generate household archetypes based on behavioural factors and patterns determined during the analysis process. The profiles of each archetype used for modelling consisted of parameters based on both the survey and published data. The details of each archetype including respective dwelling types and behavioural patterns are specified in Chapter 6.

A mid-terraced house was chosen as the base case for the application of a range of single energy efficiency technologies across the five archetypes, without dwelling change. The performance of each option was compared across the archetypes. The simulated period was between November 1st and March 31st during heating seasons, with a 30-minute time-step. The values for parameters related to retrofit measures represented the average highest efficiency that can be achieved in practice. In contrast, the values selected for dwellings such as the building envelope and system characteristics showed the real and very inefficient dwelling conditions.

The impact of retrofit measures on a dwelling's energy use and savings was then evaluated across the five household archetypes with respective dwellings. This further addressed the likely variations of performance each measure may have upon changes in dwelling and household characteristics. Combined with the test in the previous step, this was useful for evaluating whether any the variation in the performances of measures was due to dwelling characteristics or if it was rather mainly influenced by occupant behaviour.

A further evaluation was carried out on the sensitivity of the parameters associated with each retrofit measure. To assess how behavioural patterns might have an impact on the parametric sensitivity, a comparison was made between active spenders and average users. The modelling evaluations used the mid-terraced dwelling as the base case so that any change in sensitivity of the parameters would be due to behavioural changes.

In addition, the cost-effectiveness of the retrofit measures was compared and ranked among different household archetypes. Such a comparison offered insights into the optimal options for retrofit investment with respect to its paybacks. This offered a rational basis for decision-making about which measures to choose first given a limited budgets.

Finally, the research assessed the impact of a modelling approach incorporating household archetypes compared with the conventional method used for generating retrofit recommendations in EPCs at urban scale. It used Cambridge as the case study, with assumptions made about the dwellings and proportions of household archetypes. Initially, for the purpose of comparison with emphasis on behavioural variations, it was assumed that the housing stock was comprised of the mid-terraced dwellings specified previously. The energy and cost savings were then compared at both the dwelling and city levels.

3.5 Research Ethics

The Ethics Committee for the School of the Humanities and Social Sciences granted its ethical approval for this research on 19 December 2013 (see Appendix E). The research design respects the ethical code and guidelines, which concerns mainly the recruitment of participants, depersonalisation, data protection and retention. A relevant information sheet was given to all participants recruited for this research. Their consent was obtained indicating their understanding of the research project's purpose and also that they could withdraw at any point. All data was depersonalised and stored securely.

CHAPTER 4 SOCIAL PRACTICES OF OCCUPANT COMFORT

4.1 Introduction

This chapter explores the variations in social practices of occupant comfort in the home. It forms an initial exploration towards the development of energy retrofit strategies that address the performance gap. As indicated above, the approach taken in this first phase of research has been to conduct primarily qualitative investigations of fourteen households, using interviews, questionnaires, observations, photographs, diary logs and data logger monitoring. This part of the study aims to explore perceptions of comfort by the occupants, the daily behaviour of the occupants, and how the occupants interact with their home environment. Because of the university's ethical guidelines, all the case studies have been depersonalised; their names have been changed in this chapter. The results are presented in relation to the four concepts in the theoretical framework discussed in the previous chapter: meaning (4.2), composition (4.3), task (4.4) and material (4.5).

4.2 Meaning

The wide variety of definitions of comfort expressed by the interviewees illustrates the subjective nature of comfort, which has led some householders to have more energy-intensive lifestyles than others. There were also different emphases on what the most important aspect of comfort was to each individual. These demonstrated the variations in occupants' comfort practices, as well as the need to accept such variations. For example, one occupant in my study, Alex, who had a desire to settle down and start an academic career, stressed independence as an important element in comfort, in addition to bodily sensation:

> "I define thermal comfort as a warm temperature, 19-22^{o}C. No extremes of humidity, but mostly the temperature. Other kinds of comfort are harder to describe; good food, cold drinks (or hot coffee), a good night's sleep, quiet neighbourhood, a quiet night in is very comfortable. Occasionally a drink with friends, no dancing or late nights, just a pint and good conversation … The most important aspect of comfort is control; having choice over your situation so you can shape your circumstances to your mood.

> Flexibility. Financial comfort is a factor, not having to worry about keeping the lights on. Comfort is about choice, if I am told to do something, I am less comfortable. Being your own boss. Comfort is about freedom." (Interview A)

Another definition of comfort came from Catherine, a homeowner living together with her husband and children. She emphasised the emotional and functional aspects of comfort in the home:

> "Family together in the home; sense of security and cosiness/homeliness in the house. Protection, warmth and sound insulation … Ensure house is safe and secure (high quality door and window locks used consistently), pets, garden, keep temperature right for season/weather, have the right lighting (not too bright), comfortable seating and beds, uncluttered design and tidiness (but we haven't got it!), bath (!) for soaking, family meals at table, have lots of books, music available in all rooms (central system), comfortable clothes when at home, inviting friends and having parties, celebrating festivals." (Interview C)

In contrast, George, a young academic, considered that quality of life is the most important aspect of comfort. He has an apparent preference for a healthy work-life balance, including spending time with friends and enjoying leisure activities:

> "In a general definition of comfort, I'd include life quality (food quality, working hours – something between 6-8 hours per day, people sharing the accommodation with being respectful, tidy and well-behaved), job fulfilment, physical activity and social life." (Interview G)

Interviewee Lucas considers himself to be a very flexible person with some of the stereotypically English traits of stoicism and reserve, suggesting that the times that he felt genuinely uncomfortable had mostly been because of physical discomfort such as being too hot, cold, dry or noisy. He prefers to have control of situations and make himself feel comfortable; he states:

> "Privacy is very important to me and is a big part of comfort, however this is very dependent on the location and expectation. For example at home I would rather keep

all of the blinds down during the day even though this shuts out the daylight, in order to maintain privacy from the street/courtyard. Having freedom and flexibility to choose how to be comfortable in a space is important to me. This has probably a lot to do with having some control over my personal environment, and not being forced by external factors to conform to (what I believe are) unnecessary expectations." (Interview L)

Despite some common ground, the meaning of comfort was different for each interviewee to some extent. Many additional themes surfaced, such as feeling relaxed, fulfillment, wellbeing, feeling secure, having an intellectually stimulating environment, having peace of mind and equanimity, and being in meaningful relationships with family and friends. Among the various views of what constituted comfort, environmental conditions were mentioned by all participants in different forms, such as having reasonable warmth, appropriate lighting, fresh air, cleanliness, lack of noise or bad smells, easily accessible toilet and shower, isolated room and the right background sound.

> "Not too cold, not too hot, with light, with the right background sound (e.g. for working, complete silence; for relaxing, music chosen by me), no unwanted smells, right degree of intimacy (e.g. for work, anyone; for relaxing, only close friends or partner) … Temperature is a very important aspect of comfort, but maybe natural light is more important." (Interview B)

> "Pleasant average temperature, good indoor air quality, sufficient daylight levels, all adjustable." (Interview J)

> "The absence of discomfort … a mental state where you would not be distracted from the adversity of environment, unawareness of the surrounding." (Interview N)

Their various interpretations of the notion of comfort influenced the way the occupants behaved in pursuit of comfort, and this behaviour extended well beyond heat balance equation and physiology theories.

> "I adapt my clothes or the room/space around me to control the environmental conditions, and psychological comfort can come from exercise or distracting one's

self from the day to day routine through seeing friends or watching comedy. Finishing pieces of work can provide relaxation or comfort, as it's satisfying to complete a task. Getting fresh air and being outdoors can be one way to be comfortable, so can sitting in bed under a duvet and watching a film. Having a beer with friends can also be relaxing, as can being in familiar or inspiring surroundings. I may talk to my family on the phone to relax; I find comfort in finding out how they are doing. Catching the train to London and catching up with old friends can also be comforting as it helps to feel connected with people. In terms of personal achievement or focus, I find work and research to be stimulating and comforting, as it can motivate and inspire me to keep working in a particular direction. Wearing my favourite jumper or clothes can also prove comforting. Feeling like I'm achieving something towards my future be it academic, financial, ethical or health related can be fulfilling too." (Interview E)

The ways in which people conduct their everyday life in relation to comfort can have higher or lower energy implications. For example, in my study, compared with those who spent extensive time outside the house, the householders who stayed inside most of the time tended to heat the house longer. Similarly, the individual interpretations of "comfortably warm" were matters of personal taste, and resulted in a wide range of thermostat settings. It is therefore important to take each individual's comfort preference into account instead of benchmarking household performance solely against energy references.

4.3 Composition

The interviewees belonged to various household types, sizes, and tenure types. Household types included "single", "couple" and "family with children"; household sizes ranged from "single" to four people; and tenure types could be either "owner occupied" or "privately rented". These various household compositions influenced the comfort practices of occupants, such as how they used and controlled the heating facilities, as well as how they occupied rooms and how many household members occupied certain rooms. For example, Ethan's room heating settings were controlled by his housemates from a central boiler, causing him to feel too hot in the evenings; he had to open the windows to cool down.

Ethan commented: "It is on a set timer, a setting configured by my housemates. [The setting is] 8-10am, 3-3.20pm, 5-5.20pm and 7-11.30pm … all housemates seem happy with it. [I open windows] when I get too hot, typically in the evening around 11pm; maybe 1 hour, sometimes all night if it's too hot (once or twice a week during the winter month)." (Interview E)

Similarly, Natalia (Interview N) lived in a single privately rented room in a shared Victorian house and her landlord controlled the heating system. She believed that the heating was automatically on 7-9am and 6-12pm. Thinking it would be too cold after midnight to stay up without heating, she used a portable heater to keep warm. She also opened her windows for a few hours in the morning and half an hour after dinner to let out any cooking smells and to let in fresh air. Speaking of her heating situation, Natalia stated:

> "I can't control [it] but as it is usually set at the appropriate temperature, I don't care. Nothing to complain about [the heating temperature] … generally warm, but no heating around midnight makes it quite cold for late-night style people; but overall heating length across the year is great – 7-9 months out of a year there is heating." (Interview N)

In contrast, Catherine had full control over her house's heating settings. She set the heating up through the central programmer located in the living room, taking into account the whole family's schedules as well as her own health concerns. According to Catherine:

> "Permanent heater run on controller with thermostat at 19^{o}C except for 06.45–09.00, at 21^{o}C. On thermostat and programmer, it comes on when my husband gets up at 06.45 and then again when everyone else gets up at 08.30ish. Also I put it on if cold, for as long as necessary." (Interview C)

Depending on the relational dynamic of the people living together, there could be situations where one householder had more influence over energy practices than another or others. Nevertheless, when more than one person lived under the same roof, the performance of the whole house was naturally affected by the sum of all the people living in it. In the case of Alex and his wife, both parties participated in setting the periods of heating and temperature and were happy about it:

> Alex added: "Relax on the couch with TV or book, I put on a sweater or blanket, my

wife usually turns up the heat. … Relaxing is usually just being at home with my wife and having a quiet night in. We love going to a movie, having a nice dinner, simple boring old married couple. Weekends are breakfast in bed followed by a slow move to the couch for more coffee." (Interview A)

These examples show that coordination and compromises occur when various household members live together with various internal dynamics. Different tenure types can also influence comfort practices, determining, for example, whether the energy bill is included in the rental and how much autonomy the occupant has over the residence. The heating thermostat is malfunctioning in Jessica's dwelling, so she keeps the windows open, while setting the heating in her living room on full power. She feels that the high temperature is good for her children, but does not consider it urgent to find a technician to fix the thermostat, since the energy bill is fixed; there is no financial incentive for such an action.

4.4 Task

The interviewees perform different tasks at various locations and times, where their comfort needs differed. These activities determine which room is occupied and how. By monitoring the results for the various participants, one can find that some of the temperatures and times in the different rooms and varied depending on the householder's tasks or activities. Certain patterns were detected. For example, bedroom temperature is higher in the evenings compared to the daytimes, and living rooms peaked in the early evenings when cooking and eating dinner were taking place. Nevertheless, there were some discrepancies, for example, an empty room or house sometimes still consumed energy because of unattended equipment, such as heating or lighting.

Alex's example illustrates how occupants' daily activities affect home heating practices (Figure 4.1). On an ordinary weekday, Alex (Interview A) wakes up at around 7am and has breakfast with coffee. Then he goes into town or stays at home reading for an hour. He works at his home office from 9am to noon, then goes to the gym for exercise, and has lunch at home. Later he continues to work in the home office until early evening. When his wife comes home, they have dinner together and then sit on the sofa watching TV. They go to bed at around midnight. However, throughout the day when it was monitored, the temperature in his bedroom remained at around 17^{o}C or 18^{o}C, whereas in the living room it went from 16^{o}C in the early morning to 21^{o}C in late evening. During his working hours, the temperature in his office room stayed between 16.5^{o}C and 17.5^{o}C, with a slight increase (1^{o}C) in the evening and a drop (2^{o}C) in the early morning.

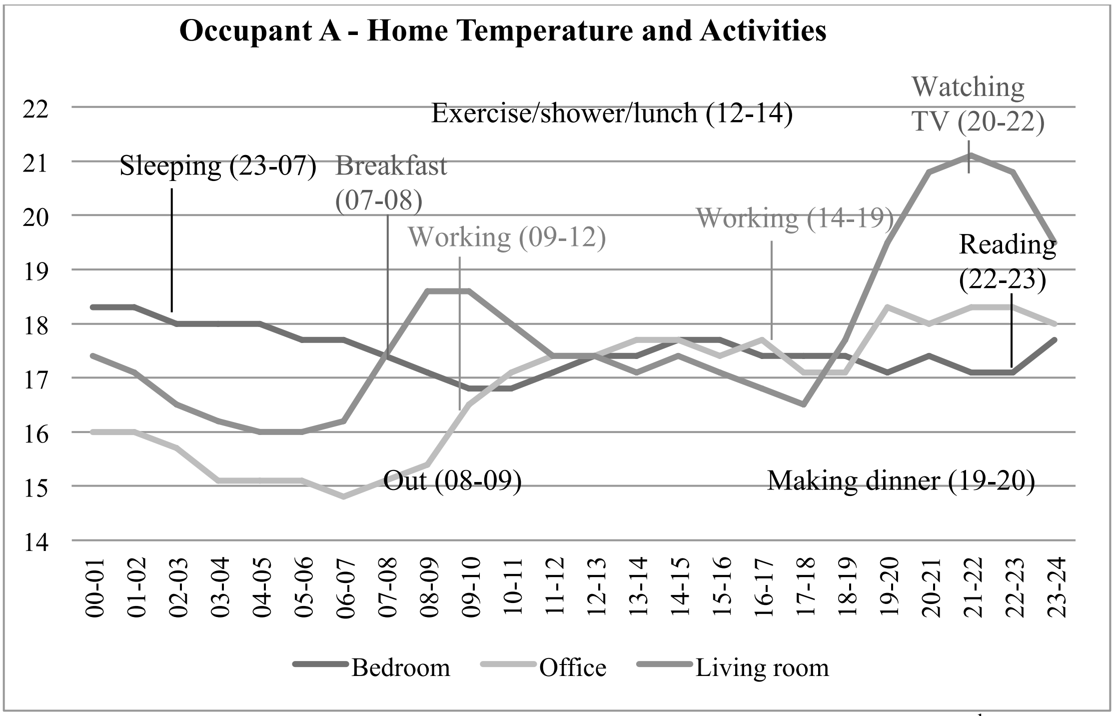


Figure 4.1 Occupant A: Home temperature and activities on Monday Feb 3rd 2014

Another example is a typical day in the life of Lucas, who normally works from home (Figure 4.2). He spends most of his time working on his laptop at the desk in the living room, apart from the time he spends sleeping in the bedroom at night. Sometimes he goes out a few times during the day, to the office or into the city centre for shopping. He usually cooks at home, mainly simple meals (e.g. pasta or noodles) with sauce and side dishes. According to Lucas, the heating is set through the thermostat and is usually on for about 6 hours per day, when necessary. However, the monitored data shows that the temperatures in his living room/kitchen (20^{o}C -22^{o}C) and bedroom (19.5^{o}C - 21^{o}C) remained constant for the most part, with peaks occurring at around midnight, which might be due to heat gains from the tumble dryer or dishwasher.

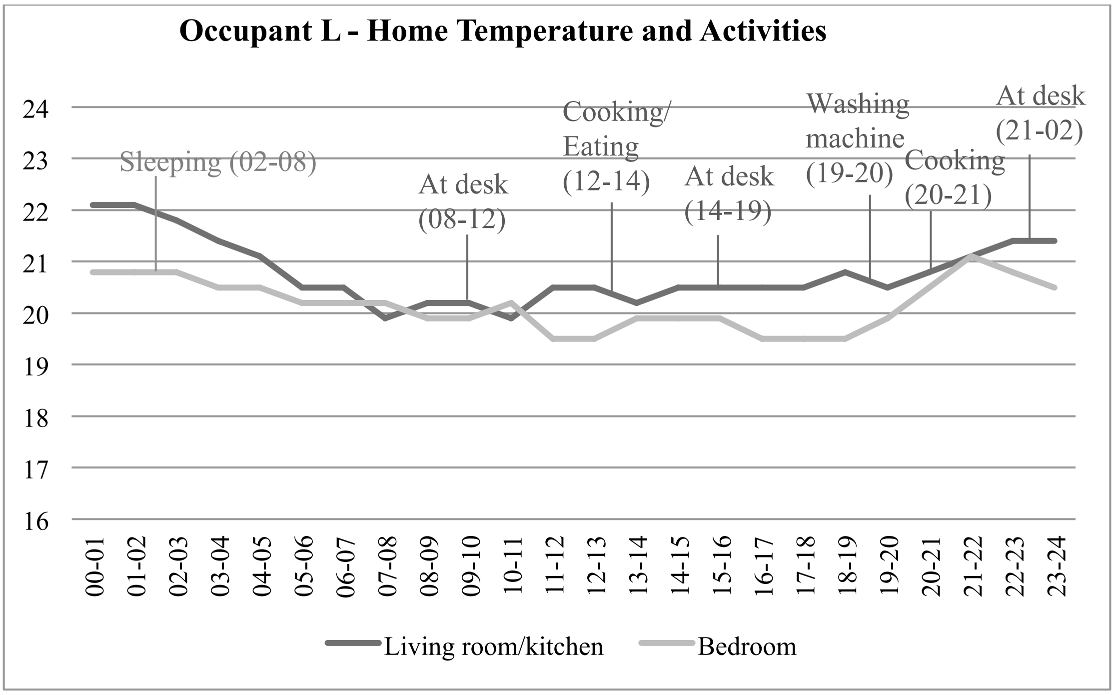


Figure 4.2 Occupant L: Home temperature and activities on Monday Feb 3rd 2014

In contrast, Bella's heating setting at home remains constant irrespective of her absence from the apartment. According to Bella, she and her partner consciously keep work out of the house, thus the apartment is usually empty during the day. In an ordinary weekday (Figure 4.3), Bella starts around 8-9am, goes to the office or library to work, and then comes back home early, around 5-6pm, relaxes with some leisure activities, such as playing music, cooking, chatting with a friend or her partner, and does some non work-related reading before going to bed if she still has the energy. The monitoring data at her flat showed that the temperature remained unchanged throughout the day, with 20^{o}C in the living room, 18^{o}C in the kitchen and 17.5^{o}C in the bedroom.

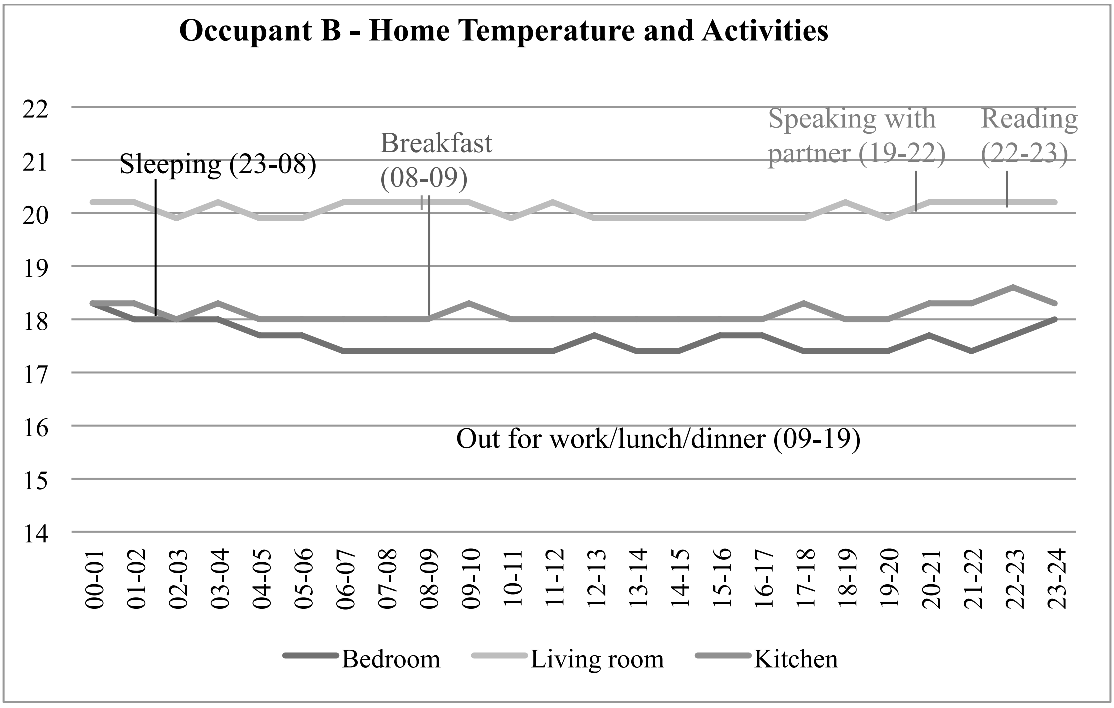


Figure 4.3 Occupant B: Home temperature and activities on Monday Feb 3rd 2014

Unlike Bella's case, Ethan has little control over the heating setting for his room. On a typical weekday (Figure 4.4), Ethan wakes up at around 7-8am, and then has shower and breakfast before going to work in the university. Typically he spends the whole day outside his home, working, exercising, having lunch and dinner. Then he comes home at around 7pm and continues to work, sometimes spending a few hours in the evening socialising or exercising in the college before coming back to sleep at around 11pm. The heating temperature in the graph shows the pre-set heating schedule on the boiler arranged by his housemates. It went from 23.5°C around midnight to 17°C in the early evening, with a slight peak at 22°C around 10am.

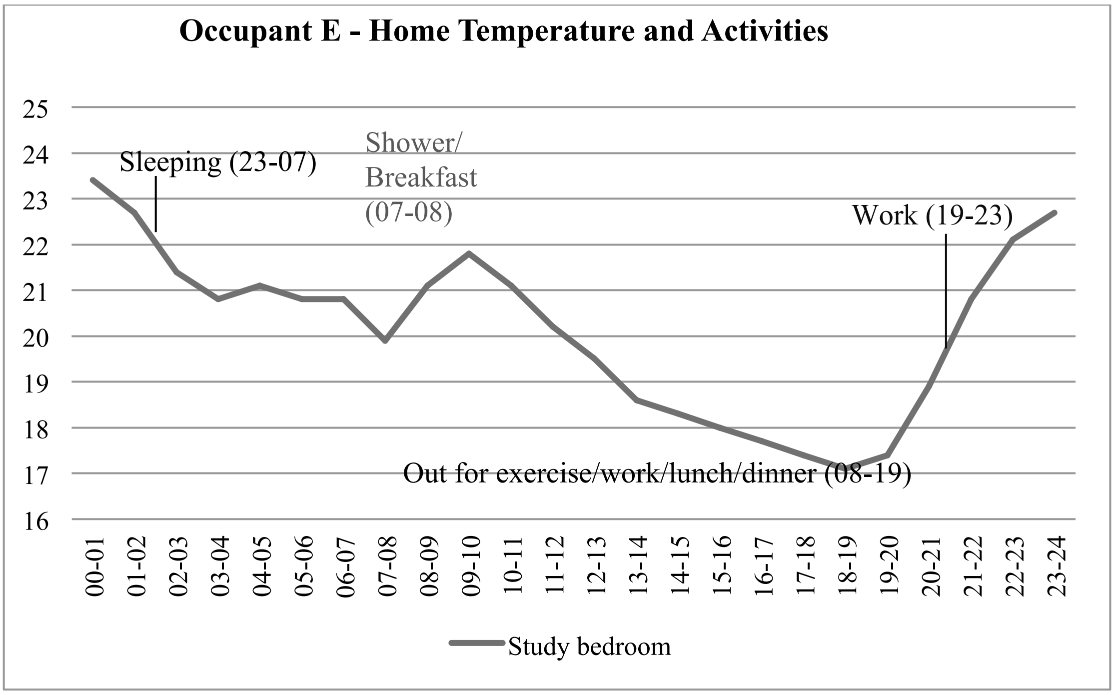


Figure 4.4 Occupant E: Home temperature and activities on Monday Jan 20th 2014

Likewise, Jessica also had limited control over her heating due to her thermostat malfunction. On an ordinary workday (Figure 4.5), Jessica wakes up at 6.30 am and has breakfast. She drops her children off by car at nursery at 7.30 am, and then cycles to work at 8 am. After a full-day of work in the office, she picks up her children and returns home at 4 pm. She usually spends two hours playing with the children and preparing for dinner until 6 pm, and then puts them to bed at 7.30 pm. When her husband comes home around that time, they have dinner together. This is followed by leisure activities and bedtime at 10 pm. The heating temperatures in both the master bedroom and the children's bedroom followed similar patterns, ranging between 18°C and 21°C in the daytime and 19°C or 20°C during sleeping hours. As for the living room and kitchen, these temperatures were much higher: between 20°C and 25°C. It is worth noting that the temperature remained high or even higher during the daytime, when no one was at home, because of a large solar gain through glazing.

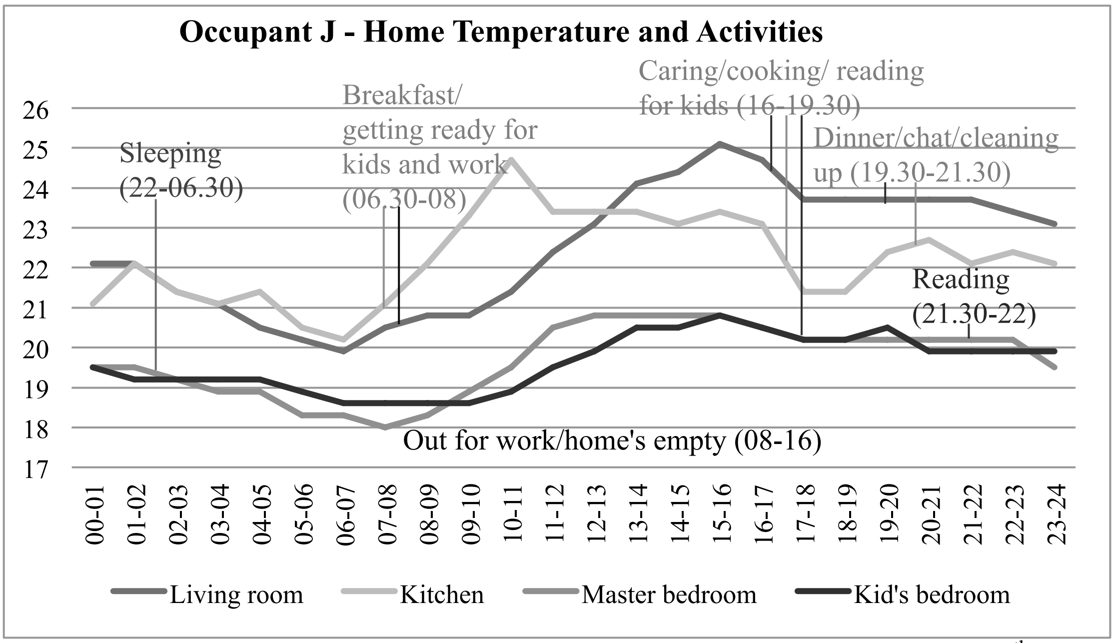


Figure 4.5 Occupant J: Home temperature and activities on Wednesday Feb 26th 2014

4.5 Material

Material served as a medium for occupants to satisfy their comfort needs. It shapes the way occupants interact with the house as well as their comfort satisfaction. These include the physical characteristics of the building, such as housing size, dwelling type and vintage, as well as the systems and appliances in the building. Five cases were illustrated below, including Ethan, Alex, Bella, Jessica and Lucas.

Ethan rents a room on the second floor of a terraced house, which is old, leaky and poorly insulated. The house was built in 1960s and has relatively small floor area. He shares the kitchen, bathroom, toilet and central heating control (in the kitchen) with three other housemates. There is no individual programmer in his own room, and the thermostat valve is malfunctioning, therefore he is unable to control the temperature in his room. His housemates set up the heating schedule in the kitchen. He often feels so hot in the evening that he has to keep the windows open to cool his room down. However, it is still too hot at night and he is thermally dissatisfied. Ethan has a comparatively low level of satisfaction with his comfort at home, especially thermal and acoustic comfort, which is directly linked to his lack of heating control and the poor insulation in the house, as the thermostat did not work in his room and the house was poorly insulated. The only physical aspects of his room that make him feel very satisfied are the window views and the ventilation. Ethan would prefer to have an isolated heating system, lockable doors, and more storage space in the house. He is also dissatisfied with his acoustic comfort and would like to have soundproofing on the walls of his room.

The building in which Alex rents a maisonette was designed in 1967. It was retrofitted after 2008, with an entire upgrade of the thermal envelope (except for the front door) and a new service system (MVHR system, electric under-floor heating, and central hot water system from solar thermal panels). His maisonette contains a living room, two bedrooms, a small office, a kitchen, a bathroom, and an entry hall. Alex is very pleased with his living environment and has a high comfort satisfaction level. He is generally happy with his housing condition, especially the indoor air quality, humidity, daylight level, and acoustic comfort. Nevertheless, he would like to have timer control for the ventilation, and some change to the artificial lighting that would create a warm feeling. He feels there is a limited ability to control the acoustic situation, especially when there are children playing outside. He also notes his lack of control over the arrangement of the house and furniture (e.g. couches and chairs). He further suggests replacing the front doors, which would make the front entryway much warmer, as well as changing the kitchen space.

Bella lives with her partner in a privately rented accommodation on the first floor of a semi-detached listed house that was built with cavity call in 1920s. Her flat contains an entry hall, living room, kitchen, bedroom, bathroom, and toilet. The house has been retrofitted with secondary glazing in her living room, kitchen and bedroom, as well as an upgrade in the CHP boiler on the ground floor for the whole house. Though the landlady controls the heating system and hot water centrally, Bella can still adjust her room temperature through thermostat controls in each room. Bella is generally satisfied with her comfort at home, especially the heating periods, humidity, cleanliness and maintenance, general living space and building design. She wishes that they had more airflow, as not all the windows can open fully and some do not open at all, partly due to burglary safety devices and heavy window sheets. In addition, she feels would like the bathroom to be ventilated more quickly after showering, and the lighting level in the hallway and bathroom to be brighter. Bella finds that the cultural differences between the UK and her birthplace cause her certain comfort dissatisfactions, particularly with regard to lighting and ventilation levels.

Jessica lives in a privately rented apartment with her husband and two children. The apartment contains a living room, two bedrooms, an office, kitchen, bathroom and toilet. Her apartment is located on the first (top) floor of the building, which was designed in the 1960s and had Grade-II listed status. The windows of the apartment were upgraded with secondary glazing before they moved in three years ago. Radiators are in each room except the bathroom and the toilet. Mechanical ventilation is available in the apartment, as well as a louvered vent on the windows for natural ventilation. She regularly opens the windows to ventilate the apartment, and uses curtains at night to prevent draughts. She is quite satisfied with her comfort in the apartment, except for certain aspects of the heating, artificial lighting and maintenance:

> "Heating not working properly, no control over it in the living room since 4 weeks so it is very hot and windows open during heating. … (There) could be more light bulbs and more effective ones. … Cleanliness and maintenance could be better, … the College provides maintenance but they have been unable to fix the leaks for example in the small bedroom, the surfaces would need a retrofit (e.g. the carpet)." (Interview J)

Lucas and his wife lived in a privately rented flat comprised of a living room with kitchen facilities, a hallway, bathroom and bedroom. It is located on the ground floor within a multi-level block. The flat had under-floor heating from a gas boiler, and thermostats to adjust the heating in each room. They open the window in the living room (facing a courtyard) often in winter, even when it is very cold, to ventilate the flat when cooking and to release excess heat (mainly from the tumble dryer and dishwasher). Because the heating system is very slow to react (1-2 hours), it sometimes overshoots and becomes too hot inside, so they turn it off and open the window to reduce the temperature. Lucas is generally satisfied with his comfort at home, despite the indoor air quality, window openings, daylight level, and control of noise. In addition, he finds it difficult to adjust the heating periods properly because the flat takes so long to warm up, and the internal gains have such a big effect that the temperature is often too high. As for the air quality, he explains that the fans are not particularly effective, and the privacy/security issues concerning a ground floor flat mean that they cannot often leave the windows open. Also, their street-side windows cannot be kept open, so the ventilation is not satisfactory, nor is there visual comfort. And due to the need for privacy, they keep the window blinds drawn most of the time, so their amount of daylight is relatively low.

4.6 Summary

This chapter has presented the findings of the study of occupants' social practices of comfort at home associated with consumption. The study used social practice theory to re-contextualise potential retrofit interventions, with a conceptual shift revealing the links between various practices, material infrastructure, social and power relations, as well as individuals' perceptions. These links were conventionally overlooked when designing retrofit strategies. For example, existing retrofit recommendations have often been technological and economic oriented, whereas the social and psychological aspects have not been fully recognised or incorporated. The analysis of the households using practice theory revealed how home retrofits as part of material infrastructure can be interlocked with other elements holding practices together, such as occupants' daily activities, preferences, social rules and norms. In order to reduce energy demand while maintaining occupant comfort, retrofit needs to be viewed and approached as part of whole bundles of practices of comfort and consumption.

Within the bundles of practices, the case study showed significant differences among occupants' comfort preferences, behaviours, dwellings and social dynamics. Thus, to negotiate and transform the practices, there are potentials for households to be grouped according to their common characteristics that constitute practices for a more targeted approach. Examples can be busy singles outside home most of time or caring mother warming up the home for her children. Variations in such occupant comfort and behaviours can lead to the development of household archetypes, which represent different optimal energy demand reduction strategies. This study derived a framework for quantifying such variations: meaning, composition, task and material. It has shown how these four elements can be mutually influenced by each other, as well as how differences in these elements may require distinct retrofit approaches. The structural elements uncovered the different ways of understanding comfort and its connection with household energy-related behaviour. They informed the essential parameters to be considered when devising instruments for grouping households. These parameters such as a combination of occupant behaviour, household and dwelling characteristics will be incorporated into the household survey and subsequent identification of archetypes in the next phase (see Chapter 5).

The adoption of qualitative research techniques captured the social practices of occupant comfort in its context. By combining questionnaires, interviews and detailed monitoring all in a single study, the results revealed multiples sources of difference among occupants' comfort practices. Carrying out the face-to-face interviews in the home settings has been helpful to validate the answers from not only verbal but also other cues derived from observations and monitoring. The findings from this empirical study highlight the need for a broader perspective using social practice theory on potential home retrofit in the context of balancing between comfort and consumption, providing a preliminary step for developing retrofit solutions for a sustainable housing stock.

CHAPTER 5 HOUSEHOLD ARCHETYPES AND BEHAVIOURAL PATTERNS

5.1 Introduction

Variations in household behaviour often lead to a mismatch between actual and estimated energy performance in the home. More detailed information on behavioural variables could help in improving the prediction of energy consumption and enabling policy interventions responding to different household groups. The work described in this chapter aims to identify household archetypes and behavioural patterns in order to allow a targeted approach in energy-saving policy and retrofit improvements. It has employed a three-step statistical approach to cluster households based on empirical data collected from a household survey in Cambridge, UK. It asks the questions:

1. What are the factors underlying behaviour at home?
2. What are the behavioural patterns with regard to occupant activities and space heating?
3. What are the household archetypes with regard to behavioural patterns, comfort, energy use and household characteristics?

This chapter has been structured into three main sections relating to the results of the three-step statistical procedure, which are: (a) behavioural factors, (b) behavioural patterns and (c) household archetypes. This structure underlies the logical sequence of steps taken to derive the final outcome. First, factor analysis was used to identify behavioural factors. Statistical pattern analysis was then applied to discover behavioural patterns. Finally, a non-parametric correlation analysis was carried out in order to determine the relationship between behavioural factors and the following: household or dwelling characteristics, comfort and energy use for creating household archetypes.

5.2 Behavioural Factors

Factor analysis was used to identify the underlying factors that explain the relational structure amongst the observed behavioural variables. The type of data used for this analysis consisted of numerical continuous data. More specifically, each behavioural variable indicated length of time carrying out certain actions or activities, normally measured in hours per week. The analysis was performed using the Statistical Package for the Social Sciences (SPSS) with an extraction method using principal component analysis (PCA). The behaviour factors (clusters of inter-correlated variables) generated from the analysis were interpreted in such a way as to reveal the hidden dimensions of the observed household practices. More specifically, they were translated from the principal components extracted through PCA, representing daily schedules regarding length of time associated with use of heating, space or appliances (shown in Table 5.2). The interpretation of a factor utilises a descriptive label that comprises selecting a concept reflecting the nature of the variable measured and its relative importance to that factor (Field, 2013).

The results are shown in Table 5.1, which contains factor loadings and communalities of the thirty-two variables used for the factor analysis. Factor loadings are correlation coefficients between observed variables and latent common factors (Yang, 2012), suggesting the relationship of each variable to the underlying factor. Factor loadings usually take the form of a matrix, and are viewed as regression weights when all observed variables and common factors are standardised with unit variance (Yang, 2012). Meanwhile, communalities indicate the extent to which each variable correlates with all other variables. They are calculated by taking the sum of the squared factor loadings for that variable. Rotations were applied to the factors extracted from the data, as rotating factor loadings changes factors' reference axes and make the factors more interpretable. Varimax (Kaiser, 1958) as one of the orthogonal rotation methods was used to maximise the total variances of the squared factor loadings on all variables, resulting in each variable having either a small or large loading on each factor. Applying the Kaiser normalisation when rotating factors will take the output of non-normalised solution and report normalised solution.

Initially, the analysis was conducted without any pre-setting on the number of components. The result from this was a rotated component matrix consisting of ten components accounting for 75.60% of the variance. However, the breaking point of the scree-plot was at five or six components. A close examination of the Initial Eigenvalues of the resulting components showed that the first component explained 26.87% of the variance, the second 10.68%, the third 7.44%, the fourth 6.00%, the fifth 5.18% and the sixth to thirty-fifth less than 5% each. Thus, extraction of the five components that would account for only 56.18% of the variance was preferred, as this enhances the overview of the matrix considerably. An examination of discriminant validity through the factor correlation matrix showed that correlations between factors were lower than 0.7, and correlation coefficients between a single variable and every other variables were higher than 0.5. Consequently, the factor analysis was carried out again, selecting for the extraction of only five components. As shown in Table 2, the five columns under 'Components' show the contribution of each variable to its component. The last column contains extraction communalities, which are estimates of the variance in each variable that is accounted for by the components. The components were comprised of behavioural variables, and subsequently defined as behavioural factors.

Five behaviour factors are presented in Table 5.2, namely 'main space heating', 'auxiliary space use', 'main space use', 'auxiliary space heating' and 'use of appliances'. They were labelled based on the range of variables contained in each component, through finding shared characteristics of the variables involved. The variables contained in Factor 1 indicate a long duration of heating for the main functioning rooms. The variable 'study/office usage', which has a very different nature from other variables comprising this factor, has very low scores in factor loadings and communalities. It was thus decided to exclude this variable in the naming of the factor. The variables in Factor 2 are related more to an extensive usage of auxiliary rooms. The heating durations of conservatory and basement/storage areas were merged into this description, as they were positively correlated with the usage durations of these rooms and had a relatively smaller contribution to this factor. The variables in Factor 3 were related to the main space usage at home. The variables of sleep, exercise and social activities were merged into this description due to the significant correlation between these three variables and the usage duration of some rooms included in this factor. Factor 4 contains the variables mainly associated with the long heating duration of auxiliary space. Less usage duration of the living room might also indicate less heating duration of some of the main rooms. The relationship between the variables in Factor 5 seems to suggest an intensive use of appliances. The fact that no variable was shared between this factor and other factors indicates the independence of appliance-usage behaviour. The variable of ‘other places usage’ has very low scores in both factor loading and communalities and was thus not included in the description of this factor.

Table 5.1 Rotated Component Matrix and Communalities for 32 behavioural variables

Behavioural Variables	Components					Communalities
	1	2	3	4	5	
Living room heating	0.931					0.869
Bathroom heating	0.906					0.857
Dining room heating	0.901					0.834
Bedroom heating	0.893					0.839
Studying/office heating	0.889					0.814
Kitchen heating	0.884					0.806
Guest Room heating	0.873					0.774
Hall heating	0.864					0.774
Master bedroom heating	0.864					0.781
Utility room heating	0.476			0.456		0.676
Study/Office usage	0.428					0.32
Conservatory usage		0.899				0.83
Utility room usage		0.791				0.727
Basement/storage areas usage		0.708				0.548
Conservatory heating		0.595		0.672		0.864
Bathroom/toilet usage		0.552	0.419			0.591
Bedroom usage			0.67			0.533
Guest room usage			0.551			0.536
Sleep			0.608			0.411
Dining room usage			0.531			0.454

Exercise			0.548			0.335
Living room usage			0.445	-0.414		0.464
Social			0.529			0.397
Time spend at home			0.456			0.443
Master bedroom usage						0.43
Kitchen usage						0.258
Cooking					0.732	0.566
Personal hygiene					0.563	0.474
Housework					0.571	0.389
Other places usage					-0.461	0.29
Other places heating				0.796		0.696
Basement/storage areas heating		0.489		0.715		0.779

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Rotation converged in 8 iterations. Factor loadings < 0.4 are suppressed.

Table 5.2 Behavioural Factors

Factor	Name of factor	Variables
1	Main space heating	Living room heating; bathroom heating; dining room heating; bedroom heating; studying/office heating; kitchen heating; guest room heating; hall heating; master bedroom heating; utility room heating; study/office usage
2	Auxiliary space use	Conservatory usage; utility room usage; basement/storage areas usage; bathroom/toilet usage; conservatory heating; basement/storage areas heating
3	Main space use	Bathroom/toilet usage; bedroom usage; guest room usage; sleep; dining room usage; exercise; living room usage; social; time spend at home
4	Auxiliary space heating	Utility room heating; conservatory heating; less living room usage; other places heating; basement/storage areas

		heating
5	Use of appliances	Cooking; personal hygiene; housework; less other places usage

5.3 Behavioural Patterns

Statistical pattern analysis was used to determine behavioural patterns. This is a simple classification that uses dichotomy of the data with threshold values that represent an average level. For the purpose of making data summarisation more efficient, dichotomisation allows for simple interpretation of outcome without relying on the linearity assumption (Williams et al., 2006). The resulting categories from the classification can then be combined into a set of patterns. The strings classification shown in Table 5.3 represents the categories formed from dichotomising the data. Subsequently, these categories were combined into five behavioural patterns to differentiate occupants. The statistical pattern analysis contained six steps: (1) classifying data into categories or strings with dichotomisation; (2) combining these categories or strings into a set of patterns; (3) labelling selected patterns; (4) rearranging the cases to match the pattern groups; (5) counting the number of the cases in each group; and (6) summarising this case-counting and strings classification in tabular form (Table 5.3).

The first step was to dichotomise the factor scores (component scores) based on whether they lie above or below the mean score for the five factors. Subsequently, binary strings were formed for the 78 respondents, with each containing five dichotomous scores. Theoretically, 2^5=32 binary strings should be obtained after dichotomisation. Nevertheless, only 29 strings were found in the sample due to polarity of certain variables (Table 5.3). The three missing strings due to polarity were 11010, 11001 and 10110. These strings represented individual patterns with some more similar than others. The strings were then grouped according to their overall scores as very high, high, medium, low, very low. The thresholds were defined based on not only the overall scores, but also the score differences between space heating and space use. As a result, five behavioural patterns were defined using interpretation of the common characteristics of the grouped cases, including active spenders, conscious occupiers, average users, conservers and inactive users.

Table 5.3 shows the behavioural patterns along with the strings categorised for each pattern, while Figure 5.1 presents the five behavioural patterns in relation to the total score level of each behavioural factor. The 6 participants of Pattern I have a high score on at least four of the five factors with heating duration of main space and auxiliary space above average – we have called them *Active spenders.* People who fall into this category are characterised by their use of more space, longer durations of heating and more use of appliances. The 11 participants of Pattern II may be described by an extensive usage of space with a low score on at least one of the heating factors and a high score in at least three of the five factors – *Conscious occupiers.* This group of users tends to stay at home and use various rooms for longer durations, with less heating duration in some rooms. The largest cluster is Pattern III with 26 participants. People in this category have a high or low score on two or three of the five factors with a maximum of one high score in either auxiliary space use or main space use – *Average users.* They are semi-active in their use of space, heating and appliances, sharing an average score with the 5 factors added together. The 10 respondents of Pattern IV have a low heating duration in general but have a high score in two of the three non-heating factors – *Conservers*. This type of user is energy conscious with a shorter duration of heating and a longer duration of usage of space and appliances. The 24 participants of Pattern V have a high score on only a maximum of one of the five factors – *Inactive users.* Occupants in this category generally have a shorter duration of space usage, heating and appliances compared with average users.

Table 5.3 Behavioural Patterns with Strings Classification

Pattern [Criteria for classification]	Factor 1 Main space heating	Factor 2 Auxiliary space use	Factor 3 Main space use	Factor 4 Auxiliary space heating	Factor 5 Use of appliances	N	
Active	1	1	1	1	1	2	6
spenders [4	1	1	1	1	0	2	

or 5 high scores, high in F1 & F4]	1 1	0 1	1 0	1 1	1 1	1 1	
Conscious occupiers [3-4 high scores, high score in F2 & F3]	1 1 0 0 0	1 1 1 1 1	1 1 1 1 1	0 0 0 1 1	1 0 1 0 1	2 2 5 1 1	11
Average users [2-3 high scores]	0 0 0 1 1 1 0 0 1 1 1	0 0 0 0 0 0 1 1 1 0 0	1 1 0 0 0 0 0 0 0 1 1	1 1 1 1 1 0 1 1 0 0 0	1 0 1 0 1 1 1 0 0 1 0	2 2 3 2 2 3 2 2 1 6 1	26
Conservers [low score in F1 & F4, 2 high scores]	0 0 0	0 1 1	1 0 1	0 0 0	1 1 0	6 1 3	10
Inactive users [0 or 1 high score]	0 1 0 0 0 0	0 0 1 0 0 0	1 0 0 0 0 0	0 0 0 1 0 0	0 0 0 0 1 0	2 5 5 5 2 5	24

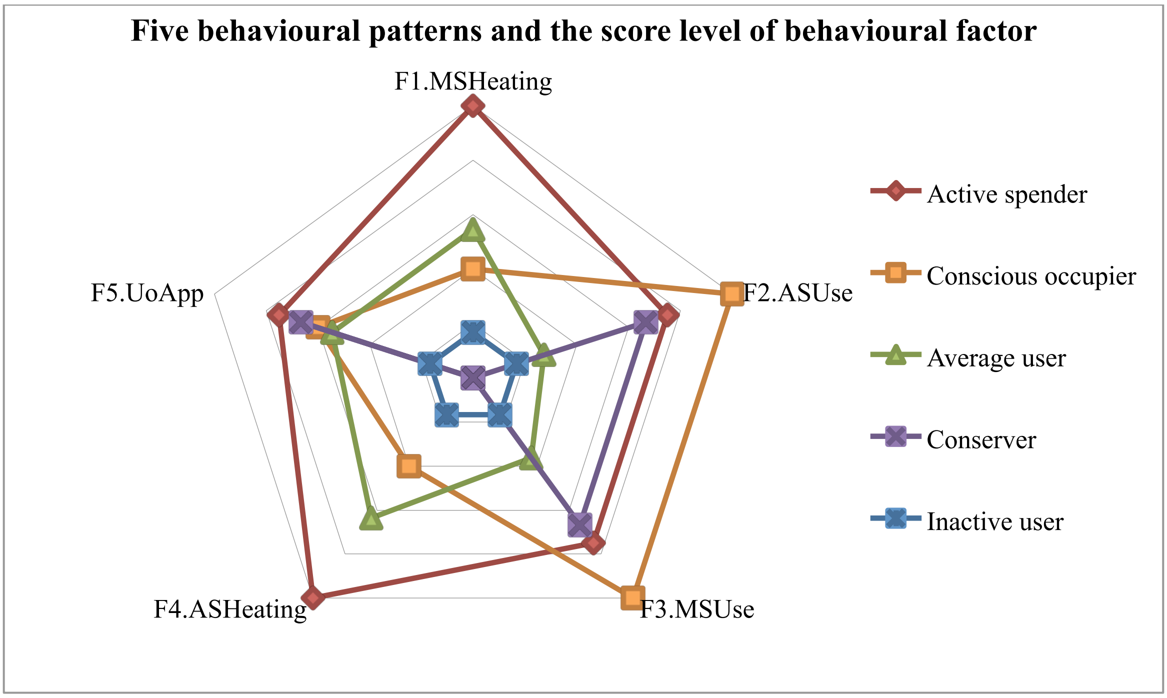


Figure 5.1 Five behavioural patterns based on the allocation of the total score level of each behavioural factor

5.4 Household Archetypes

In this section, household archetypes were developed based on the five behavioural patterns identified above as well as their connections with dwelling physical characteristics, comfort, energy use and household socio-demographic traits. A correlation analysis was carried out in order to determine the relationship between behavioural patterns and other factors. By obtaining the links between these factors, each archetype could then be distinguished and formed as a cluster of these shared traits. Comfort was measured on a scale of 1 (very dissatisfied) to 7 (very satisfied), while energy use was recorded in units of kWh/m^2. Each of the five behavioural patterns produced in the above section formed the basis for the archetypes. The behavioural variables used for the analysis were those created for each behaviour factor in Section 3.1, based on factor scores. The results from Spearman's correlation analysis can be found in Table 5.4.

The results indicated that households which scored high for 'main space heating', were mainly large families with high income living in large modern houses with high energy consumption. In addition, households which scored high for 'auxiliary space use', had a low energy use/m^2, indicating a preference for energy conservation in this group. Households with high scores for 'main space use' were mostly large young families with children living in owner-occupied houses. Households that scored high for 'auxiliary space heating' were largely retired people or students living in energy efficient dwellings. Households with a high score in 'use of appliances' were seniors living in semi-detached or detached houses.

Five household archetypes were formed corresponding to the features of behavioural patterns and associated characteristics derived above. The active-spender archetype tends to be large wealthy families living in large modern and relatively more energy efficient houses while consuming a lot of energy. The conscious-occupier archetype is more likely to be large young families with children living in owner-occupied houses that use energy consciously. The average-user archetype could cover a wider range of household types compared to the other archetypes; therefore 'working couples with moderate energy use behaviour' was selected so as to distinguish it from other groups. The conserver archetype consists of singles or couples with low income, living in small energy inefficient houses with economical energy behaviour and low energy use. The inactive-user archetype is defined as single people with full-time jobs, spending little time at home.

Each archetype was identified and described as a typical example(s) of households involved in each grouping. Such identification was intended to differentiate between the archetypes and make them distinct. As correlation analysis was employed in further distinguishing between the archetypes, a clear cut-point for all the individual data involved in the grouping was not part of the output of analysis nor was it necessary for the formation of archetypes. The archetypes chosen were therefore only defined by the behavioural factors and set of variables including household and dwelling characteristics linked to respective factors as shown in Table 5.4.

Table 5.4 Correlations between behaviour factors, comfort, energy use, household and building characteristics

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5

	Main space heating	Auxiliary space use	Main space use	Auxiliary space heating	Use of appliances
Tenure type			-.255*		
Household type	.303**		.326**		
Household size			.378**		
Occupant age			-.233*		.236*
Education level					
Household income	.241*				
Working status				.257*	
Occupation					
Environmental impact rating				.259*	
Energy Efficiency Rating				.266*	
Dwelling age	.260*				
Dwelling type					.272*
Dwelling orientation					
Floor area	.310**				
Energy use/m^2	.297*	-.298*			
Energy use	.449**				
Comfort					
Thermal comfort					

*Correlation is significant at the $P \leq 0.05$ level (2-tailed); **Correlation is significant at the $P \leq 0.01$ level (2-tailed).

5.5 Summary

This chapter has identified five different household archetypes to serve as a basis for targeted policy interventions tailored to specific socio-demographic groups regarding any reduction in domestic energy demand. These are (1) active spenders, (2) conscious occupiers, (3) average users, (4) conservers and (5) inactive users. Each of these archetypes shows specific behavioural patterns linked to household characteristics based on statistical analyses of empirical data. As a basis for determining behavioural patterns, five factors underlying occupant behaviour variables were found: (1) main space heating, (2) auxiliary space use, (3) main space use, (4) auxiliary space heating and (5) use of appliances. Significant correlations were found between the behavioural factors and energy use, household and dwelling characteristics. These correlations contributed to the profiles of the archetypes. Among these archetypes, households with a larger house, higher energy use and more complex household composition tended to have longer hours of main space heating, while larger and more complex households tended to use the main space of their dwellings for longer. Using these archetypes allows for a better integration of occupant behaviour into the technically oriented efficiency paradigm. These archetypes will be further incorporated into the next phase (see Chapter 6) for evaluating retrofit strategies. A tailored approach using household archetypes provides a gateway to developing more effective policies and low energy strategies geared towards specific households.

CHAPTER 6 RETROFIT STRATEGY

6.1 Introduction

The aim of this chapter is to explore the retrofit design implications of the household archetypes derived in the previous chapter. The hypothesis is that the optimal retrofit options vary according to different household archetypes. Modelling tests were carried out using dynamic building simulation modelling to assess and compare the effectiveness of individual retrofit measures across these five household archetypes. Furthermore, sensitivity analyses were performed to evaluate the levels of impact of retrofit measures on energy use when behavioural patterns differ. Finally, the overall energy and cost implications with regard to developing a retrofit strategy by incorporating household archetypes are illustrated.

The next section presents an outline of the household archetypes and retrofit measures specified for building energy simulation. This is followed by a comparison of retrofit energy savings across five archetypes shown in Section 6.3. Section 6.4 deals with sensitivity analysis of retrofit-related parameters in the context of both active spenders and average users. The overall impact of using household archetypes to design a retrofit strategy is demonstrated in Section 6.5 and the summary in Section 6.6.

6.2 Specifying Scenarios of Household Archetypes and Retrofit Measures

Five scenarios of household archetypes were specified: active spender; conscious occupier; average user; conserver; inactive user (Table 6.1). The profiles of each archetype consist of parameters derived from the Phase II survey, IES-VE default data as well as published data such as ASHRAE and the CIBSE Guide. The survey data served as a basis for the creation of hourly profiles as to providing the realist ranges of occupancy and usage patterns. Within these ranges, a specific profile was assigned to each archetype according to the property of that archetype (see Chapter 5, section 5.4). The profile was created based on simplifying schedules of surveyed households, supplemented by data from existing publications to represent the archetypes and make them as distinct from each other as possible. The transition of profiles from chapter 5 to 6 (e.g. Table 6.1) consisted of certain assumptions from published data and simulation software default settings. The values selected for dwellings such as the building envelope and system characteristics represent the most inefficient housing conditions. The floor plans of each dwelling are shown in Figure 6.1.

A set of commonly used energy efficiency measures (Table 6.2) was chosen for simulation modelling. This mainly tackles energy reduction on the demand side; any renewable and low carbon technologies on the supply side are not included here. The parameter values used for the measures were selected from the existing literature in academia and industry. They represented the average highest efficiency that can be achieved in practice. In addition, the amount of behavioural change resulting from the installation of smart meters and controls was assumed based on the existing behavioural pattern in each household, following the rule of minimising wasteful energy behaviour. More detailed settings on behavioural related parameters are set out in the Appendix E.

Table 6.1 Summary description of the five archetype household scenarios

Household archetype (HA) profile	Active spender (1)	Conscious occupier (2)	Average user (3)	Conserver (4)	Inactive user (5)
Dwelling type	Detached	Semi-detached	Mid-terraced	Mid-terraced	Flat
Floor area	182.22 m^2	149.83 m^2	99.41 m^2	74.92 m^2	54.33 m^2
House volume	635.07 m^3	474.58 m^3	299.98 m^3	222.37 m^3	153.38 m^3
Efficiency	EPC band D	EPC band F	EPC band F	EPC band F	EPC band F
Occupancy pattern	4 people & a pet; Unoccupied period from 08.30 to 18.00	3 people; house mostly occupied	2 people; unoccupied period from 08.30 to 18.00	1 person; unoccupied period from 09.00 to 13.00	1 person; unoccupied from 08.00 to 22.00 usually
Indoor temperature set points	24/7 on; ground floor – 21°C and first floor – 18°C	Average 7 hours/day on; ground floor – 21°C	Average 4 hours/day on; ground floor – 21°C	Average 2.5 hours/day on; 18°C	Average 1 hours/day for the main rooms; 18°C

		and first floor – 18^{o}C	and first floor – 18^{o}C		
Behavioural characteristics	Very high use of heating, hot water, appliances; high frequency of opening windows	High use of heating, appliances; open window moderately	Moderate use of heating, etc. open window moderately	Low use of heating, etc. lower frequency of opening windows	Very low use of heating, etc. lower frequency of opening windows

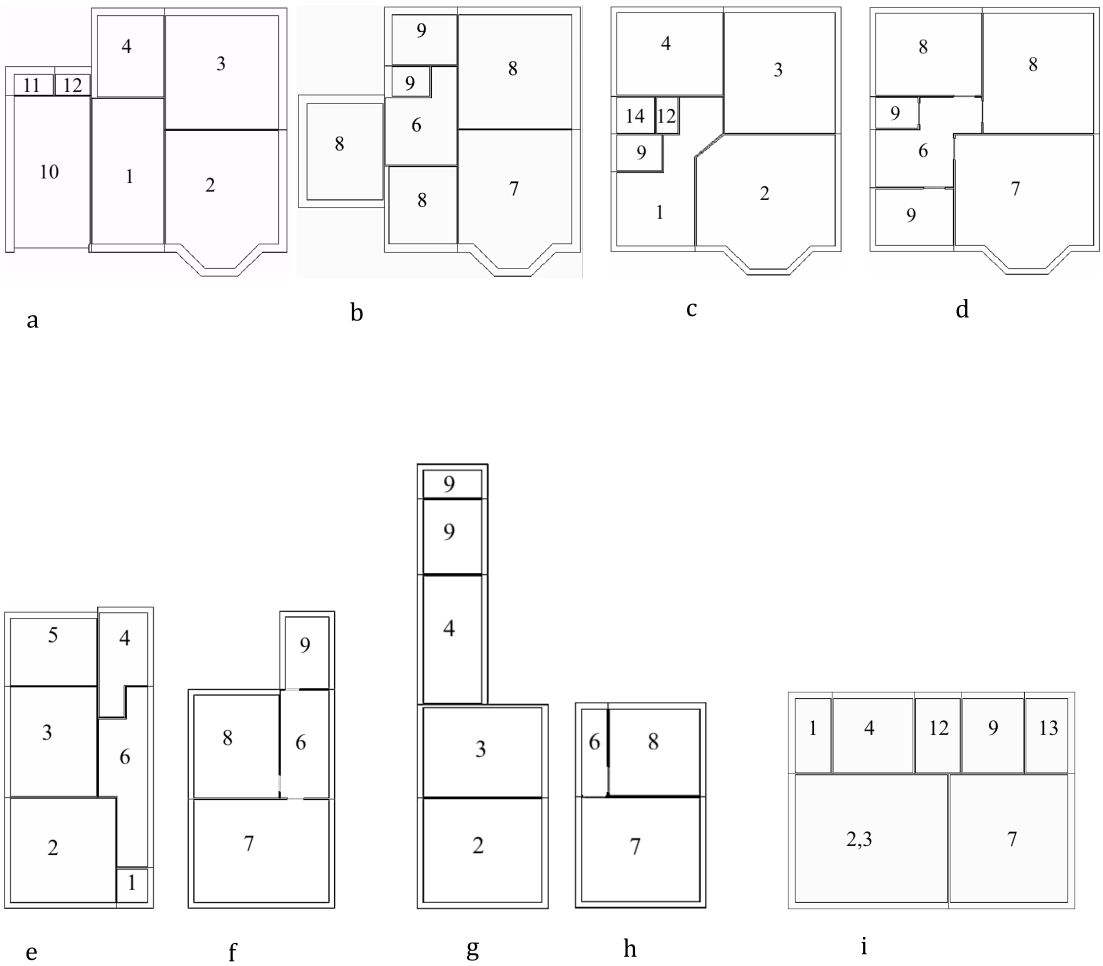


Figure 6.1 Plan of modelled dwellings for (a) HA1 ground floor; (b) HA1 first floor; (c) HA2 ground floor; (d) HA2 first floor; (e) HA3 ground floor; (f) HA3 first floor; (g) HA4 ground floor; (h) HA4 first floor; (i) HA5. (1. Hall; 2. Living room; 3. Dining room; 4. Kitchen; 5.

Conservatory; 6. Staircase circulation; 7. Master-bedroom; 8. Bedroom; 9. Bathroom/toilet; 10. Garage; 11. Fuel-room; 12. Larder/ Cupboard; 13. Closet; 14. Side-lobby)

Table 6.2 Summary description of retrofit options modelled

Retrofit measure	Input parameter	Before - EPC band F; D	After
Internal solid wall insulation	External wall U-value	2.10 W/m^{2}K; 0.91W/ m^{2}K	0.22 W/m^{2}K
Ground floor insulation	Floor U-value	1.56 W/m^{2}K; 0.77 W/m^{2}K	0.25 W/m^{2}K
Roof/loft insulation	Roof U-value	2.30 W/m^{2}K; 1.32 W/m^{2}K	0.11 W/m^{2}K
Window insulation	Window U-value	4.80 W/m^{2}K; 1.93 W/m^{2}K	0.89 W/m^{2}K
Ceiling insulation	Ceiling U-value	1.09 W/m^{2}K	0.16 W/m^{2}K
Heating system upgrade (boiler and radiator upgrades) *	Seasonal Coefficient of Performance	0.5432	0.81
Tank and pipe insulation	DHW delivery efficiency	0.6	0.90
Smart meters and controls	Heating length and temperature	See Table 6.1 Heating pattern	See occupancy patterns (Table 6.1); reduced heating length/space

* It is assumed that the boiler /main heating system use natural gas.

6.3 Comparing Energy Savings

A mid-terraced house (Figure 6.1e and 6.1f) was chosen as the base case for the application of a range of single energy efficiency technologies (Table 6.2) across the five archetypes without dwelling change. The performance of each option was compared across the archetypes (Figure 6.2). The simulated period was between November 1st and March 31th during heating seasons, with a 30-minute time step.

The impact of retrofit measures on dwelling energy use and saving was further evaluated across five household archetypes with respective dwellings. This further addressed the likely variations of performance each measure may have upon changes in both dwelling and household characteristics. Combined with the test in the previous step, this was useful for evaluating whether the variation in the performances of measures was due to dwelling characteristics or if it was rather mainly influenced by occupant behaviour.

The estimated performances of individual energy efficiency measures across different household archetypes are compared in Figure 2 and Figure 3. The initial energy uses (in MWh/yr) of the five archetypes modelled in the mid-terraced house ranged widely: 1) 82; 2) 43; 3) 31; 4) 24; 5) 21. Whereas in different dwellings, these (MWh/yr) values were: 1) 82; 2) 64; 3) 31; 4) 30; 5) 2. In both scenarios, the whole house energy saving potential from each measure tended to be larger in households with higher initial energy use. In particular, the performances of some measures varied markedly across the archetypes. This was especially the case with smart meters and controls, external wall insulation, as well as heating system upgrades. For example, with external wall insulation applied to the mid-terraced dwelling, active spenders could save more than 40 times the amount an inactive user would save. Furthermore, it appeared that the optimal rankings of retrofit measures varied more significantly when the gap between the initial energy consumptions of the archetypes was larger. For example, both active spenders and conscious occupiers benefited most from smart meters and controls along with several building system upgrades, whereas inactive users were most suited to only heating system upgrades and/or tank and pipe insulation.

The performances and rankings of energy efficiency measures changed due to variations in household behaviours (Figure 6.2) and dwelling characteristics (comparing Figure 6.2 and Figure 6.3). For the archetypes modelled in the base case, smart meters and controls were the top option for active spenders, while heating system upgrades ranked first for the rest of the archetype households except for inactive users who were more prone to energy use reduction by tank and pipe insulation. Wall insulation was the second most effective for active spenders and ranked third for the rest of the archetype households. Heating system upgrades remained influential across all households, despite slight variations among the top ranked measures. Tank and pipe insulation was also comparatively effective, especially for lower energy consuming households. The remaining measures were of relatively little impact on home energy savings, with loft or roof insulation being the least effective option. For archetypes modelled with respective dwellings, heating system upgrades triumphed across all households. The ranking of options varied slightly compared with that in the base case, particularly for inactive users, who made only small savings.

Any building system upgrades and external wall insulation produced considerably higher energy savings than the rest of the measures, especially for archetypes having relatively higher initial energy consumption levels. Despite the variance in their rankings, these retrofit measures remained the top four most influential options among different archetype households, except for inactive users who were only affected by building system improvements, depending on their dwelling characteristics. The rest of the measures on building envelope insulation in comparison saved much less energy. They were especially ineffective in the lower energy use archetypes such as conservers and inactive users, where savings from these insulations went down to almost zero. Among these less efficacious options, ground floor insulation and window insulation produced relatively higher energy savings, with loft/roof insulation being the least effective.

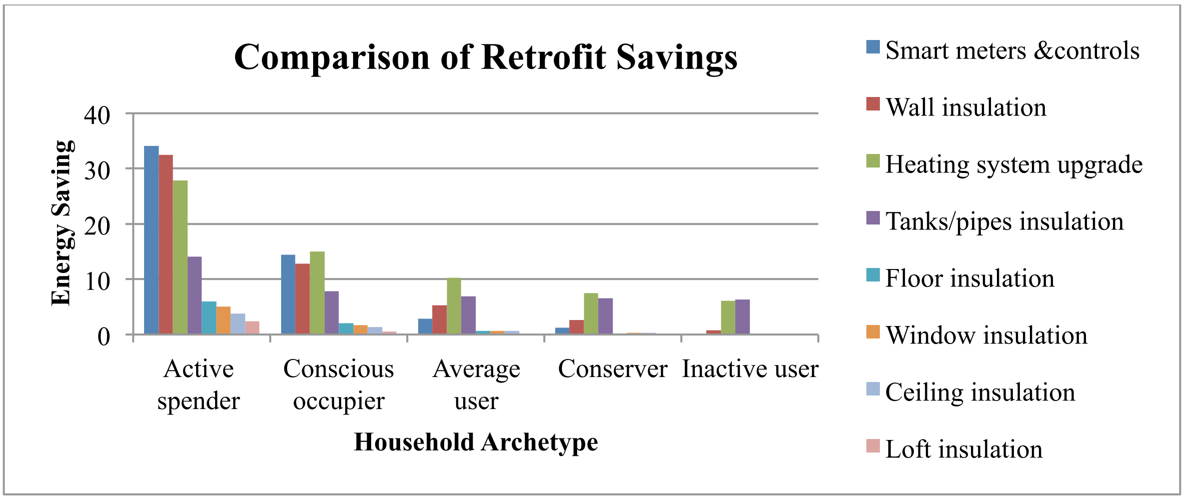


Figure 6.2 Comparison of retrofit energy savings (MWh/yr) across five archetypes in mid-terraced dwelling

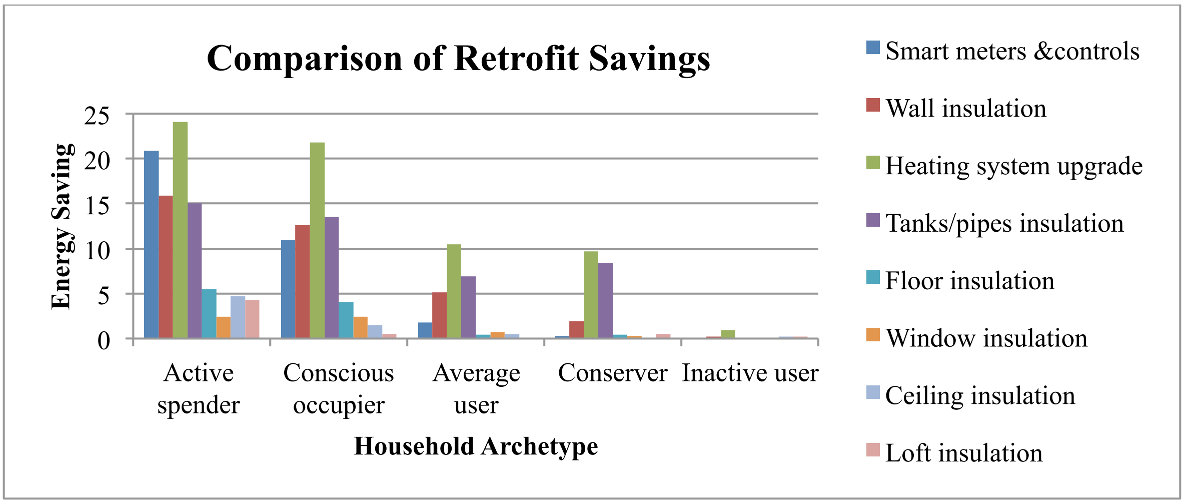


Figure 6.3 Comparison of retrofit energy savings (MWh/yr) across five archetypes in respective dwellings

6.4 Sensitivity Analysis

Sensitivity analysis is the study of how the variation in the output of a model depends upon the input information (Cheng and Steemers, 2011). This section applies sensitivity analysis to further evaluate how the impact of retrofit measures on home energy performance might vary in different household archetypes. It examines the relative impact of retrofit-related parameters on energy use with the one-factor-at-a-time method. Following suggestions from the literature, the finite-difference approximation approach was adopted and an increment of + 1% change was used (Saltelli et al., 2000; Firth et al., 2010). As in the previous section, the mid-terraced house (Figure 6.1e and 6.1f) was chosen as the base case. Table 6.3 shows the nominal values assigned to each parameter, based on the average value between the lowest and highest possible ranges. When testing each parameter, the rest of the settings were based on the conditions before retrofit, for each household type scenario.

A comparative analysis of parametric sensitivity was performed, including sensitivity analyses of the retrofit-related parameters for active spenders and average users, respectively. Initially the impact of each retrofit measure on energy consumption was assessed when the behavioural characteristics of the base case were based on active spenders. Then we ran the analysis again for average users. Finally, the sensitivity of each retrofit-related parameter was calculated and compared between the two household archetypes (Figures 6.4 to 6.22).

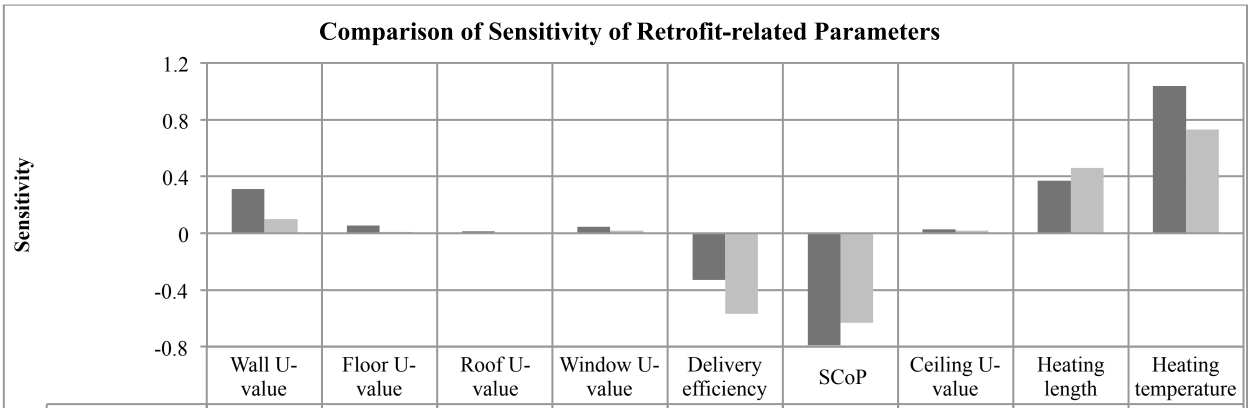
A comparison of sensitivity analyses between active spenders and average users revealed that the impact of retrofit measures on dwelling energy performance varied with different behavioural patterns (Figure 6.4). While the majority of the parameters had higher sensitivity for active spenders, the sensitivity of heating length and delivery efficiency was lower. In addition, heating length ranked higher than delivery efficiency for active spenders, which was the opposite for average users. Moreover, a comparison among the retrofit parameters indicated that heating temperature had the most profound impact on dwelling energy use for both household types. The sensitivity of heating temperature was 1.04% for active spenders and 0.73% for average users. In other words, a 1% increase in heating temperature led to a 1.04% increase in energy use for active spenders and 0.73% for average users. Other parameters also had relatively high sensitivity, including seasonal coefficient of performance (SCoP) (-0.79% and -0.63%), delivery efficiency (-0.33% and -0.57%), heating length (0.37% and 0.46%) and external wall U-value (0.31% and 0.10%). The rest of the parameters were proportionately insignificant in terms of their influences on dwelling energy use and subsequently their subsequent energy saving potentials, such as floor U-value (0.053% and 0.011%), window U-value (0.046% and 0.018%), ceiling U-value (0.026% and 0.02%) and roof U-value (0.016% and 0.0036%).

Table 6.3 Range of input nominal values used in the sensitivity tests

Retrofit measure	Input parameter	Nominal value*	Test range
Internal solid wall insulation	Wall U-value	1.16 W/m^2K	±80%
Floor insulation	Floor U-value	0.91 W/m^2K	±75%
Loft insulation	Roof U-value	1.2 W/m^2K	±90%
Window insulation	Window U-value	2.85 W/m^2K	±75%
Tank & pipe insulation	DHW delivery efficiency	75%	±20%
Heating system upgrade	Seasonal Coefficient of Performance (SCoP)	0.6766	±20%
Ceiling insulation	Ceiling U-value	0.46 W/m^2K	±80%
Smart meters & controls	Heating length	12 hrs	±100%
	Heating temperature	21^{o}C	±25%

* A nominal value has been assigned based on the average value for the parameter of the base

case before and after retrofit. When testing each parameter above, the other settings stay the same as base case values and the medium energy behaviour scenario.



	Wall U-value	Floor U-value	Roof U-value	Window U-value	Delivery efficiency	SCoP	Ceiling U-value	Heating length	Heating temperature
Active spender	0.31	0.053	0.016	0.046	-0.33	-0.79	0.026	0.37	1.04
Average user	0.10	0.011	0.0036	0.018	-0.57	-0.63	0.02	0.46	0.73

Figure 6.4 Comparison of sensitivity of retrofit-related parameters for active spenders and average users

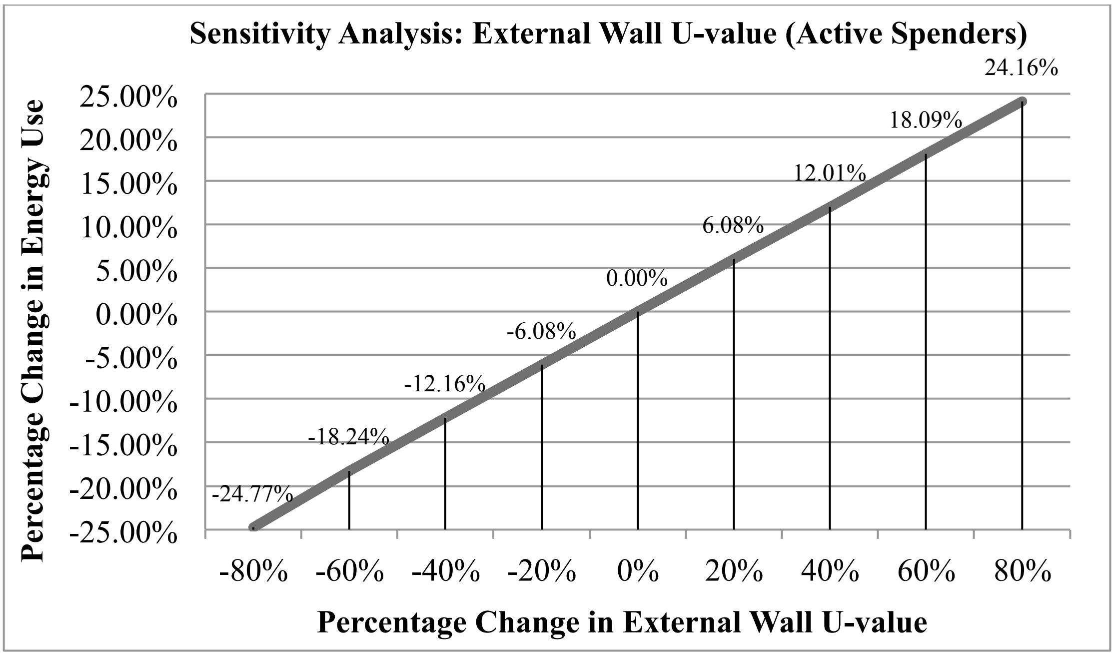


Figure 6.5 Response of energy use to external wall U-value change for active spenders (It shows that 1% increase in Wall U-value can lead to about 0.3% increase in energy use for active spenders)

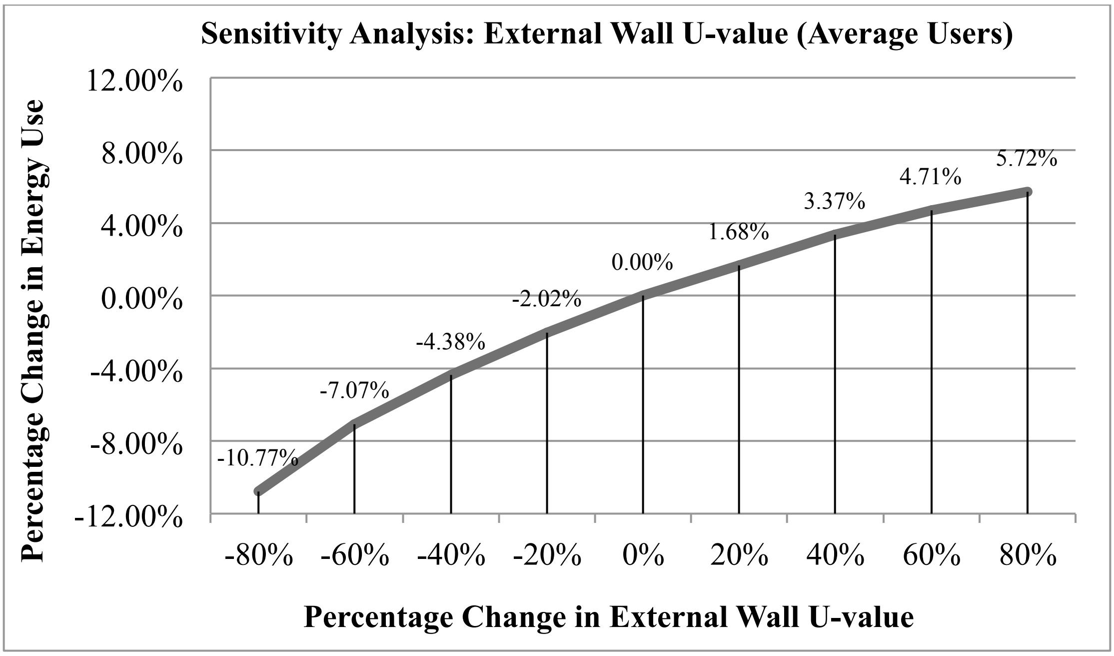


Figure 6.6 Response of energy use to external wall U-value change for average users
(It shows that 1% increase in Wall U-value can lead to around 0.1% increase in energy use for average users)

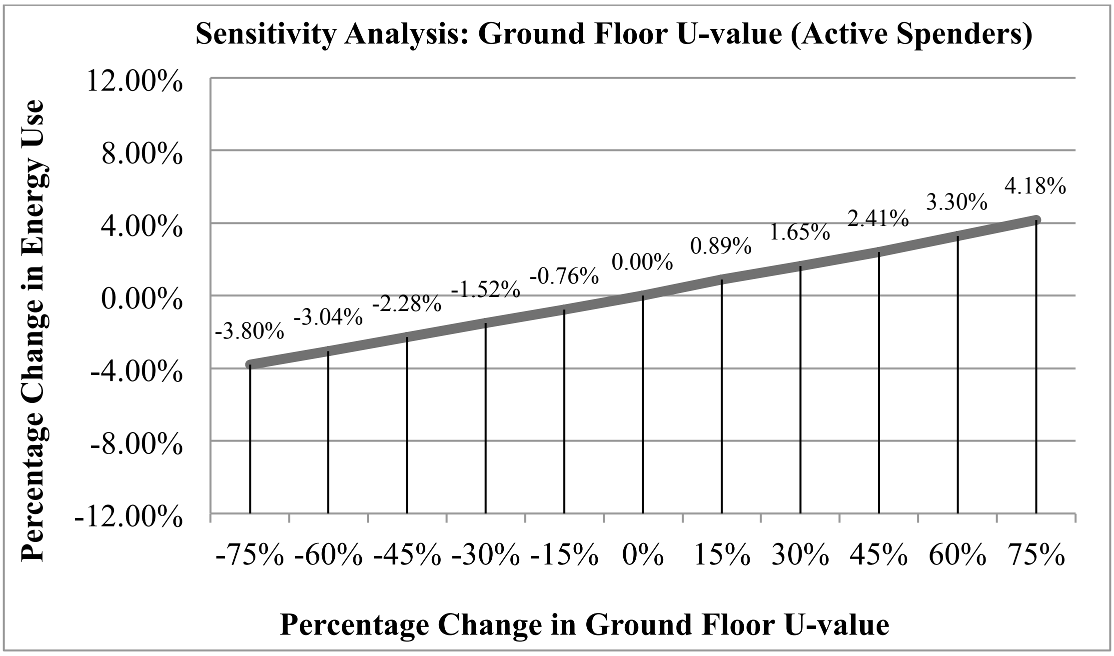


Figure 6.7 Response of energy use to ground floor U-value change for active spenders
(It shows that 1% increase in Ground Floor U-value can lead to around 0.05% increase in energy use for active spenders)

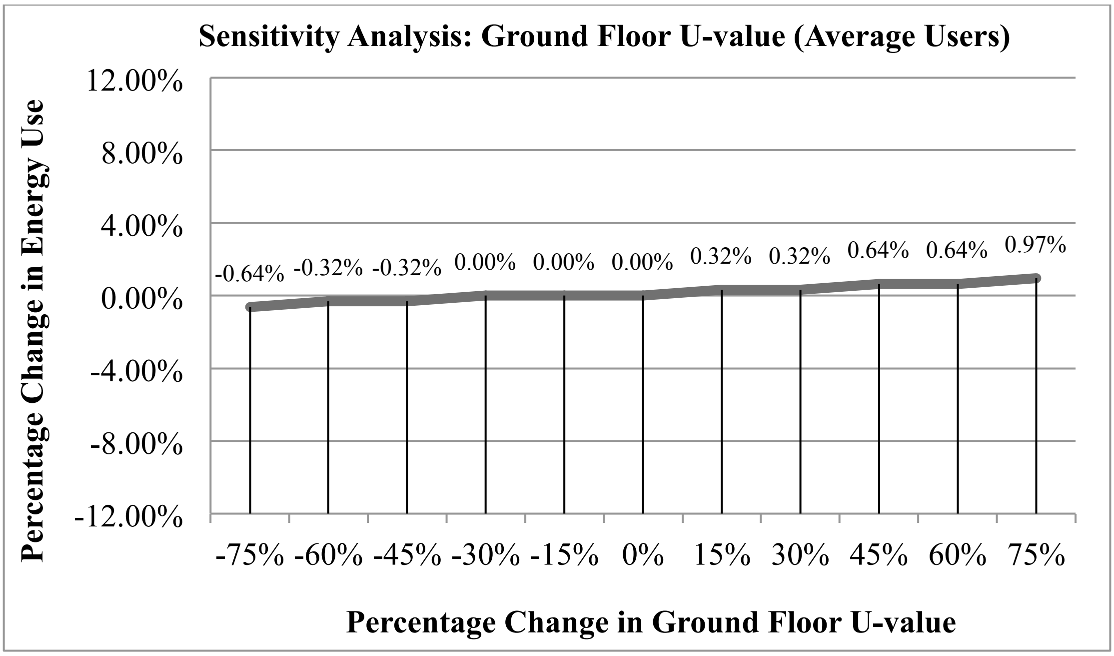


Figure 6.8 Response of energy use to ground floor U-value change for average users
(It shows that 1% increase in Ground Floor U-value can lead to around 0.01% increase in energy use for average users)

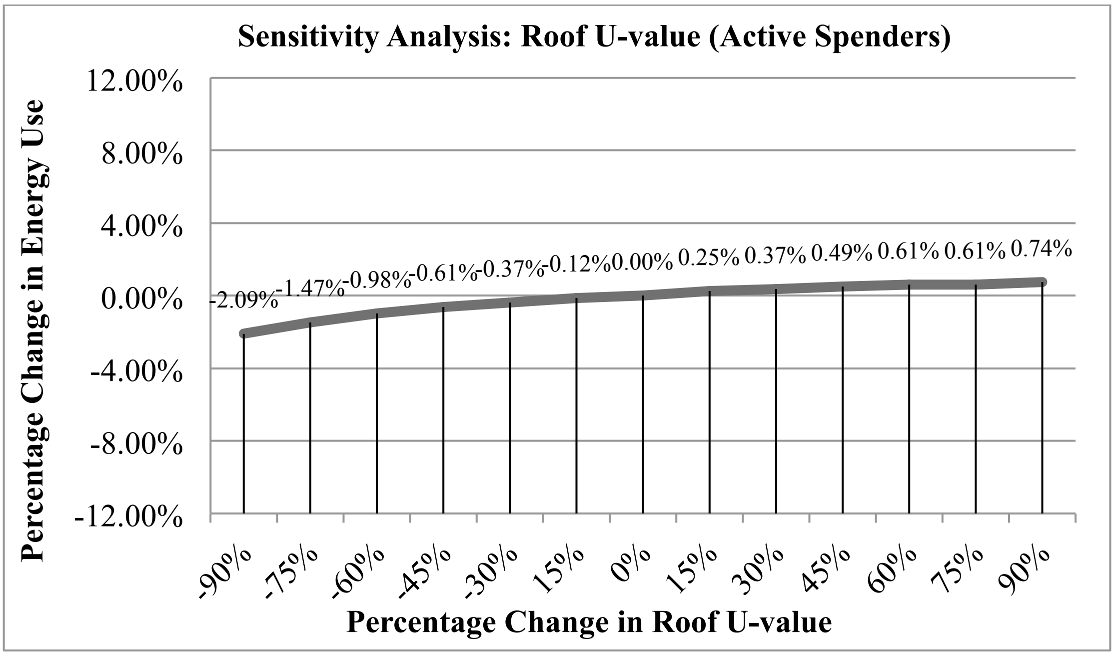


Figure 6.9 Response of energy use to roof U-value change for active spenders
(It shows that 1% increase in Roof U-value can lead to around 0.01% to 0.02% increase in energy use for active spenders)

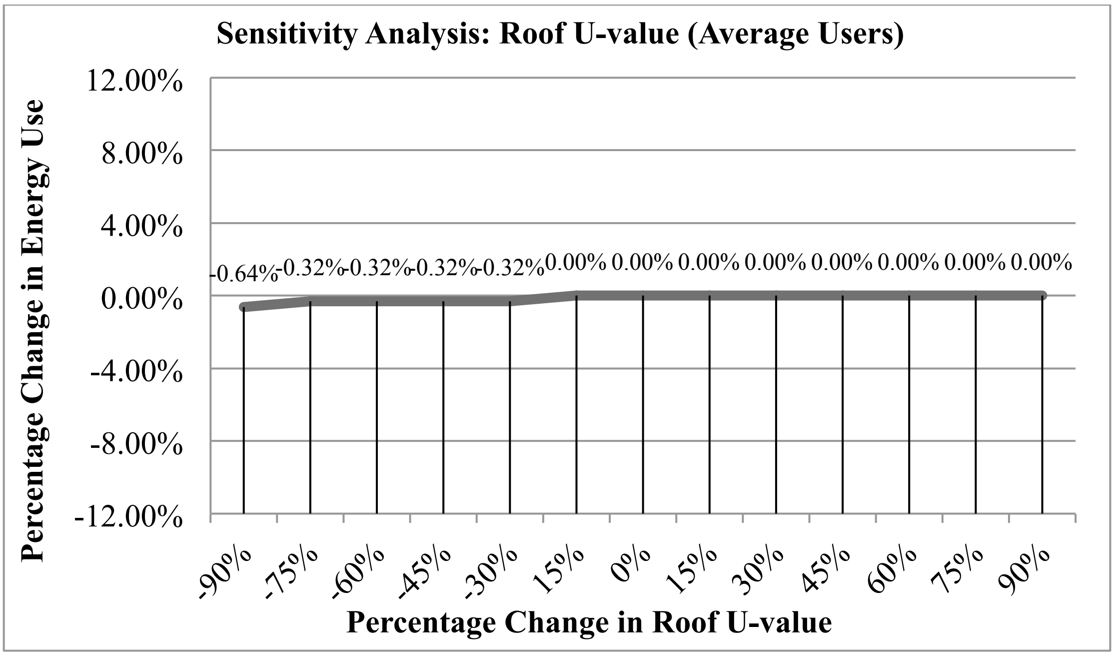


Figure 6.10 Response of energy use to roof U-value change for average users
(It shows that 1% increase in Roof U-value can lead to maximum 0.007% increase in energy use for average users)

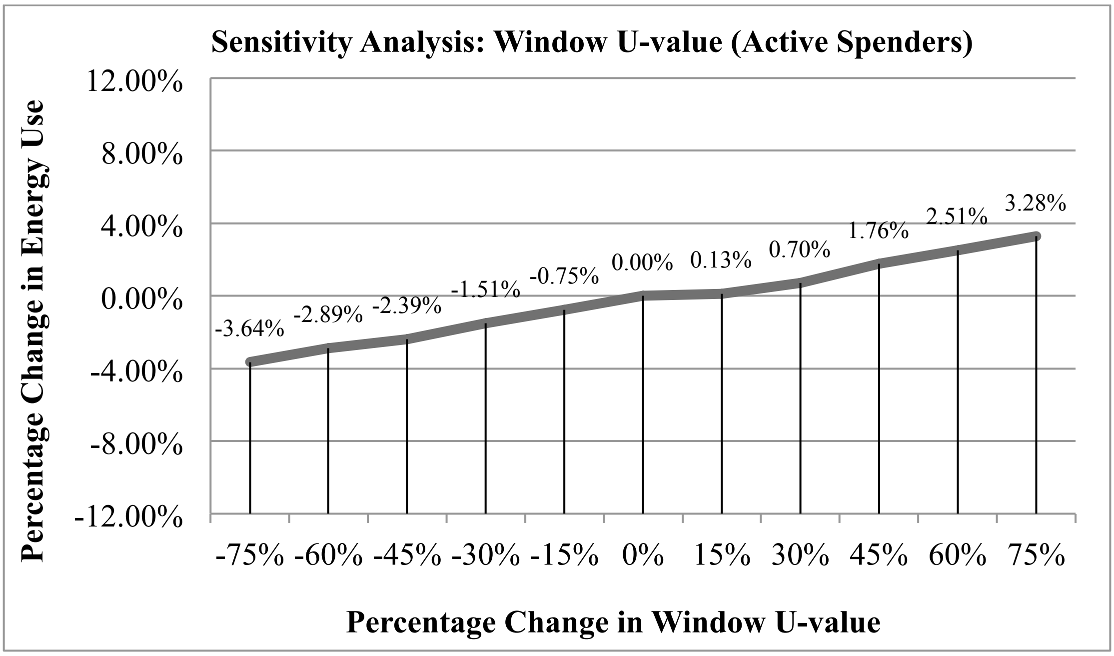


Figure 6.11 Response of energy use to window U-value change for active spenders
(It shows that 1% increase in Window U-value can lead to around 0.04% to 0.05% increase in energy use for active spenders)

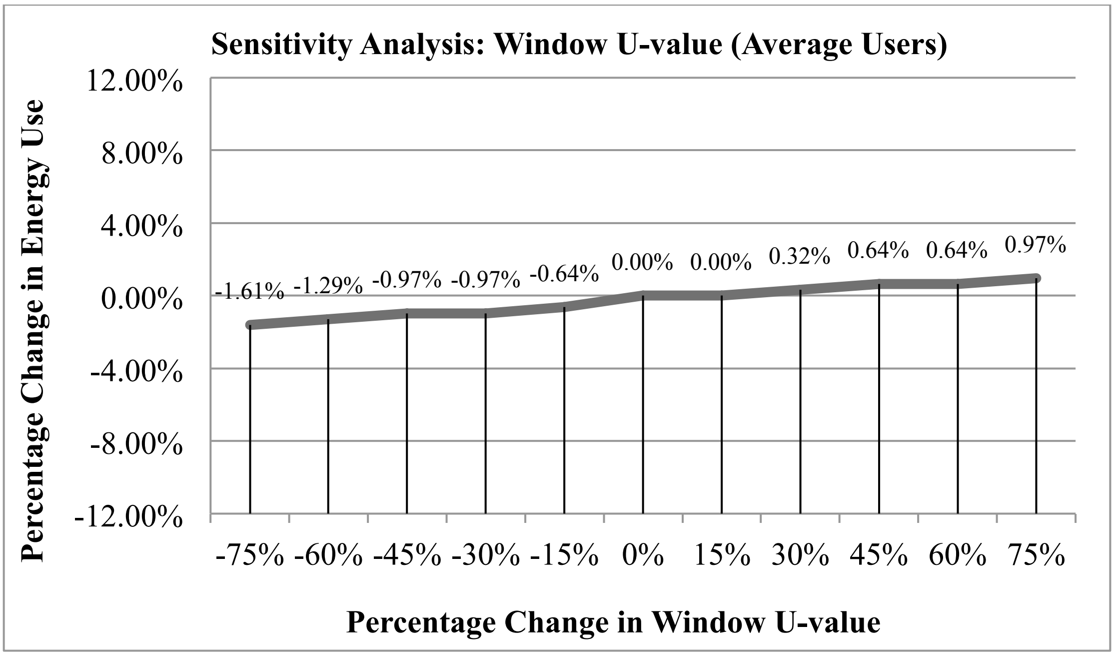


Figure 6.12 Response of energy use to window U-value change for average users
(It shows that 1% increase in Window U-value can lead to 0.01% to 0.02% increase in energy use for average users)

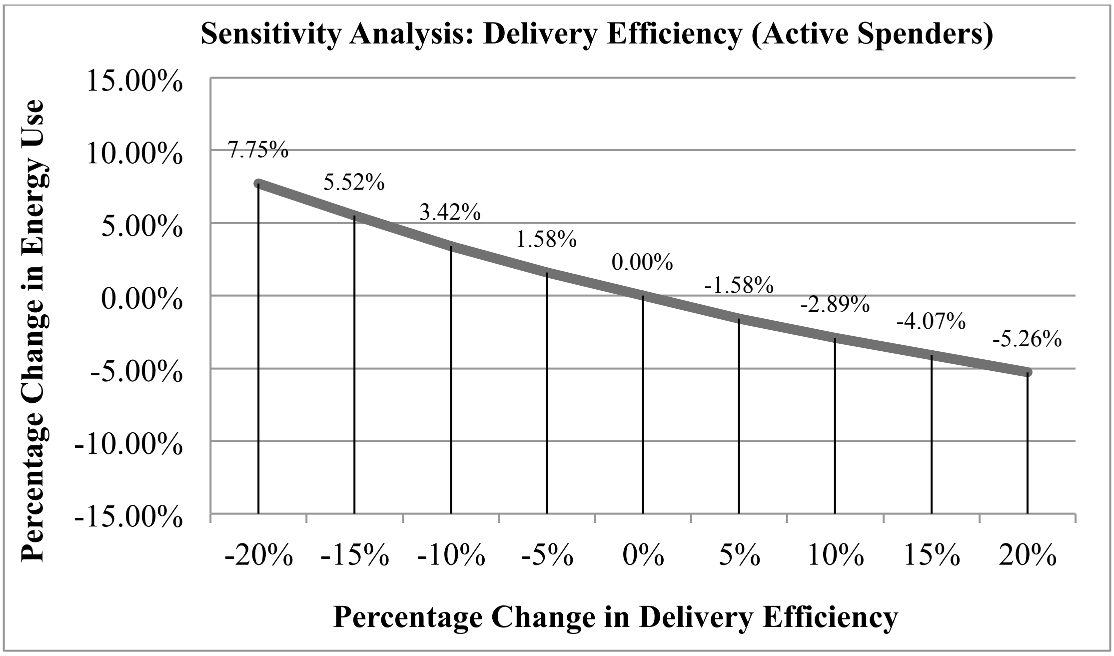


Figure 6.13 Response of energy use to delivery efficiency change for active spenders
(It shows that 1% increase in Delivery Efficiency can lead to around 0.3% to 0.4% decrease in energy use for active spenders)

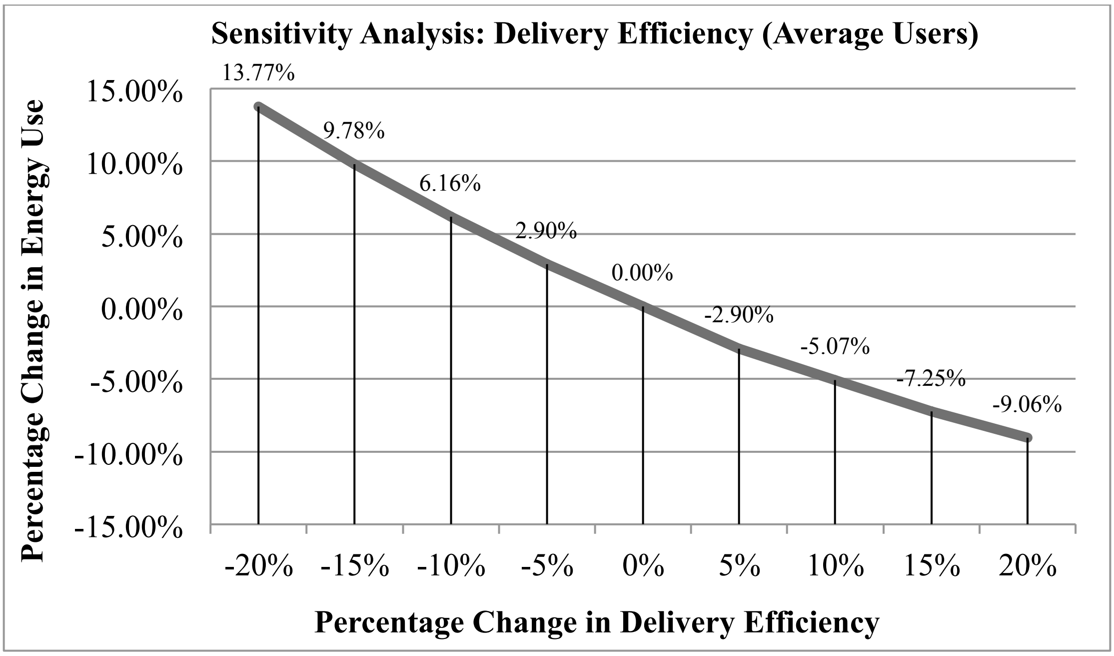


Figure 6.14 Response of energy use to delivery efficiency change for average users (It shows that 1% increase in Delivery Efficiency can lead to 0.5% to 0.7% decrease in energy use for average users)

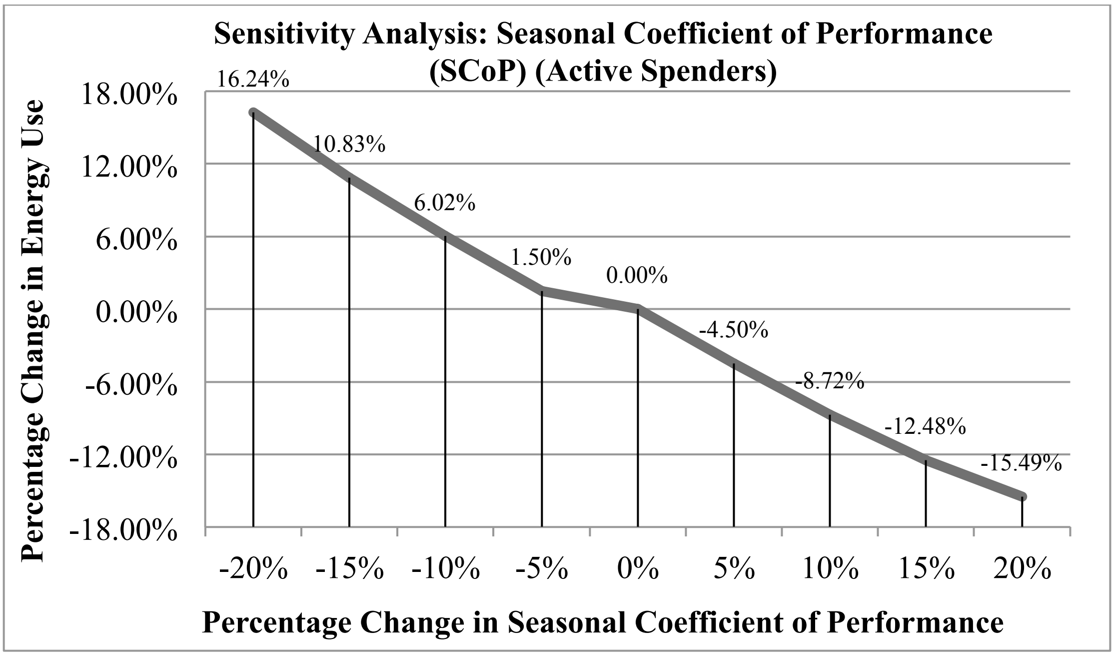


Figure 6.15 Response of energy use to SCoP change for active spenders (It shows that 1% increase in SCoP can lead to around 0.8% decrease in energy use for active spenders)

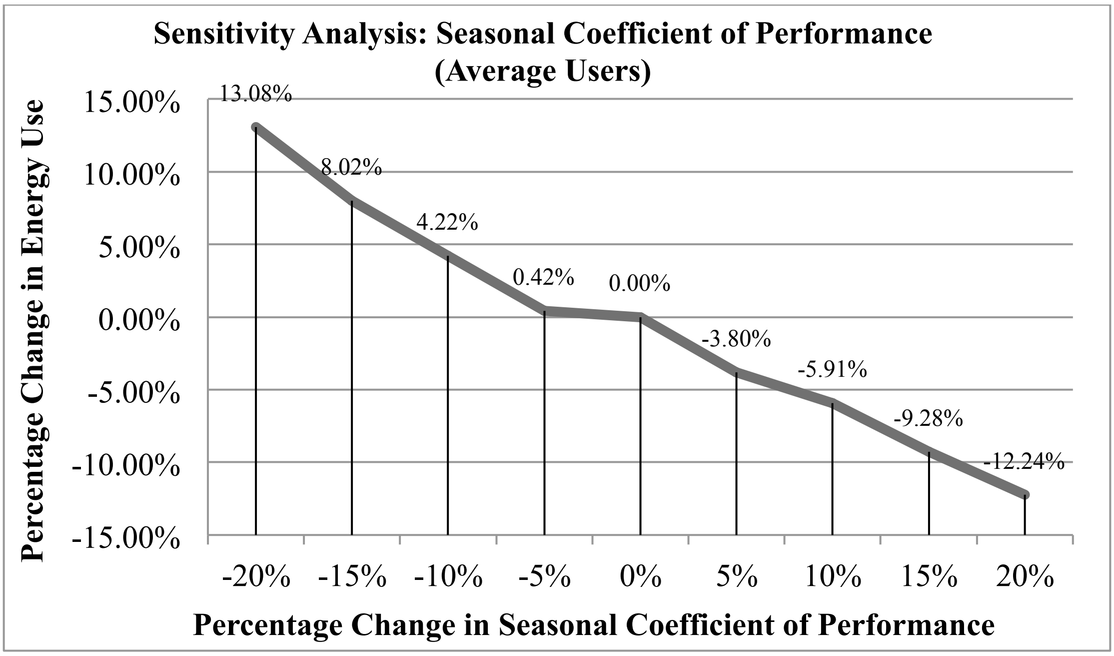


Figure 6.16 Response of energy use to SCoP change for average users

(It shows that 1% increase in SCoP can lead to 0.6% to 0.7% decrease in energy use for average users)

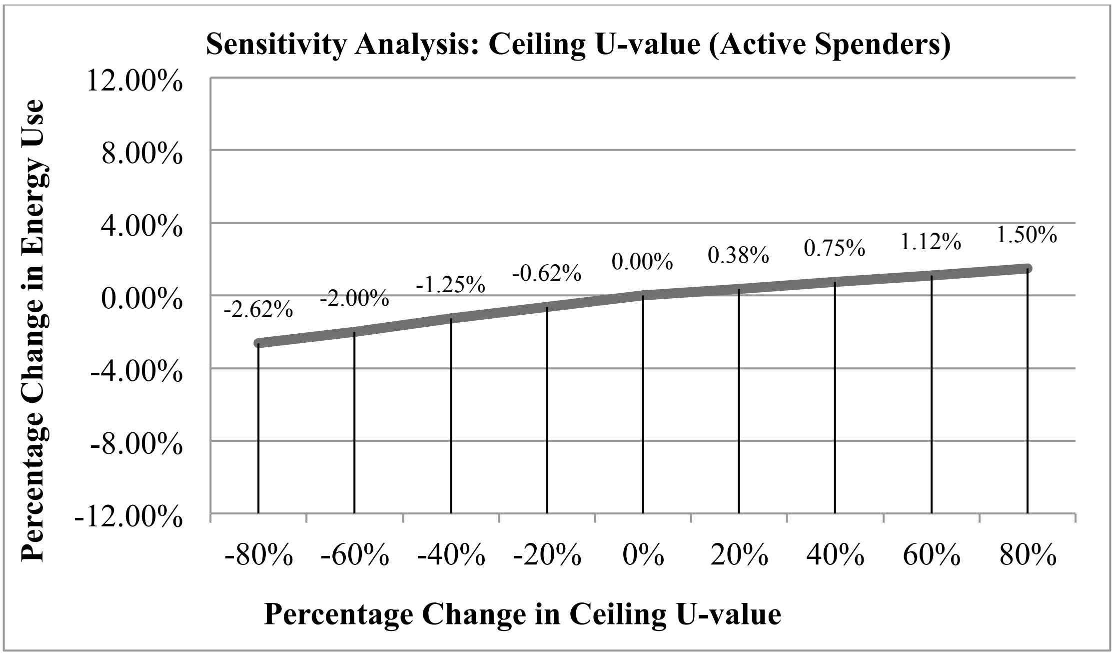


Figure 6.17 Response of energy use to ceiling U-value change for active spenders

(It shows that 1% increase in Ceiling U-value can lead to around 0.02% to 0.03% increase in energy use for active spenders)

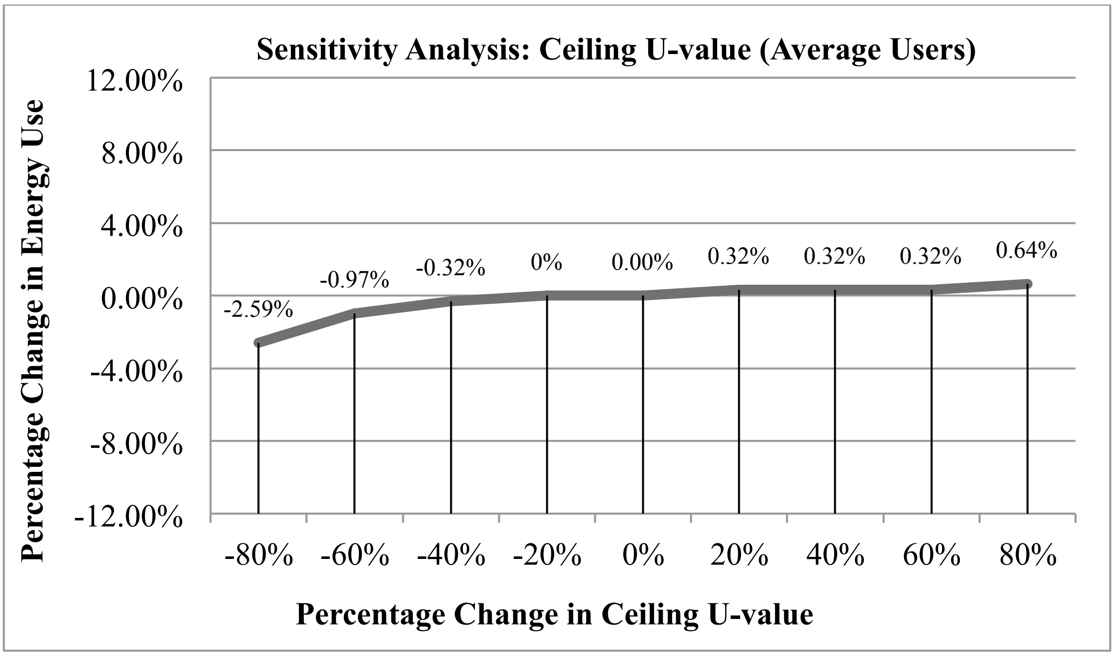


Figure 6.18 Response of energy use to ceiling U-value change for average users
(It shows that 1% increase in Ceiling U-value can lead to 0.01% to 0.03% increase in energy use for average users)

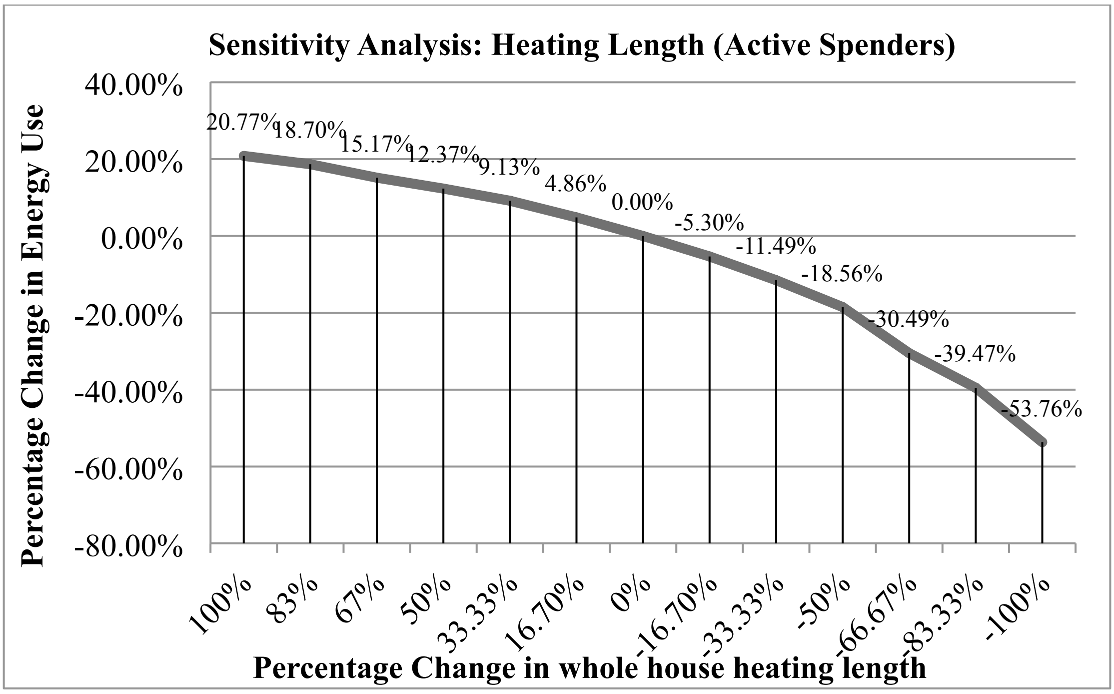


Figure 6.19 Response of energy use to heating length change for active spenders
(It shows that 1% increase in heating length can lead to around 0.2% to 0.5% increase in energy use for active spenders)

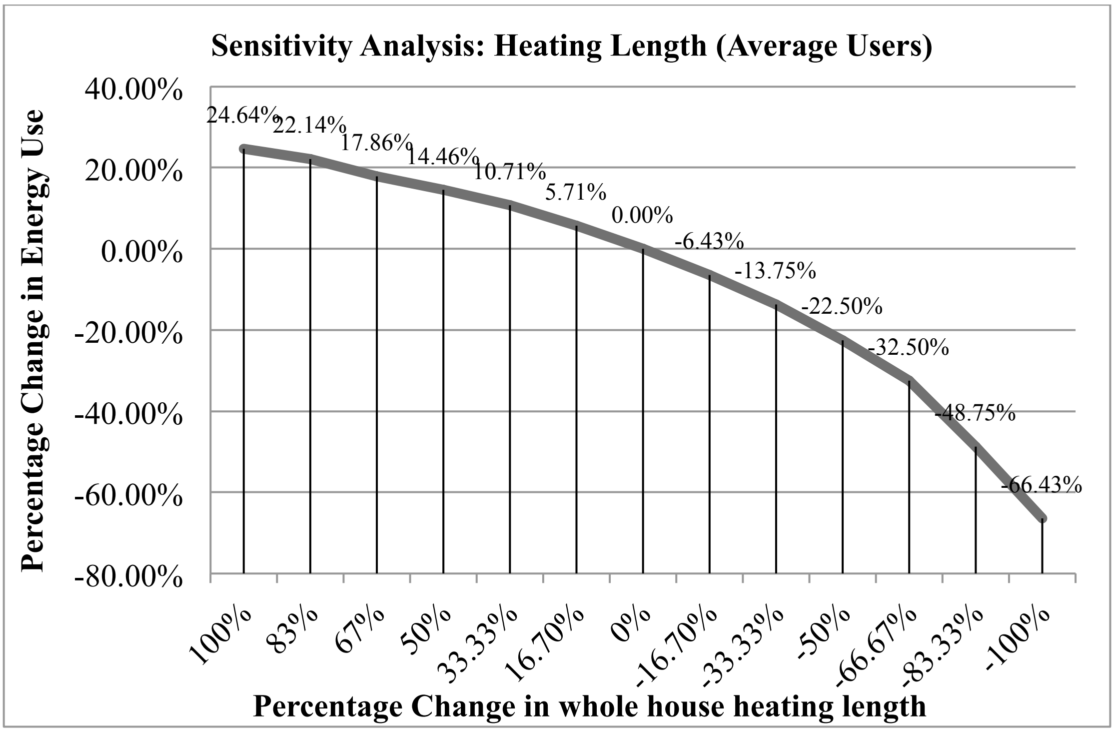


Figure 6.20 Response of energy use to heating length change for average users
(It shows that 1% increase in heating length can lead to around 0.2% to 0.7% increase in energy use for average users)

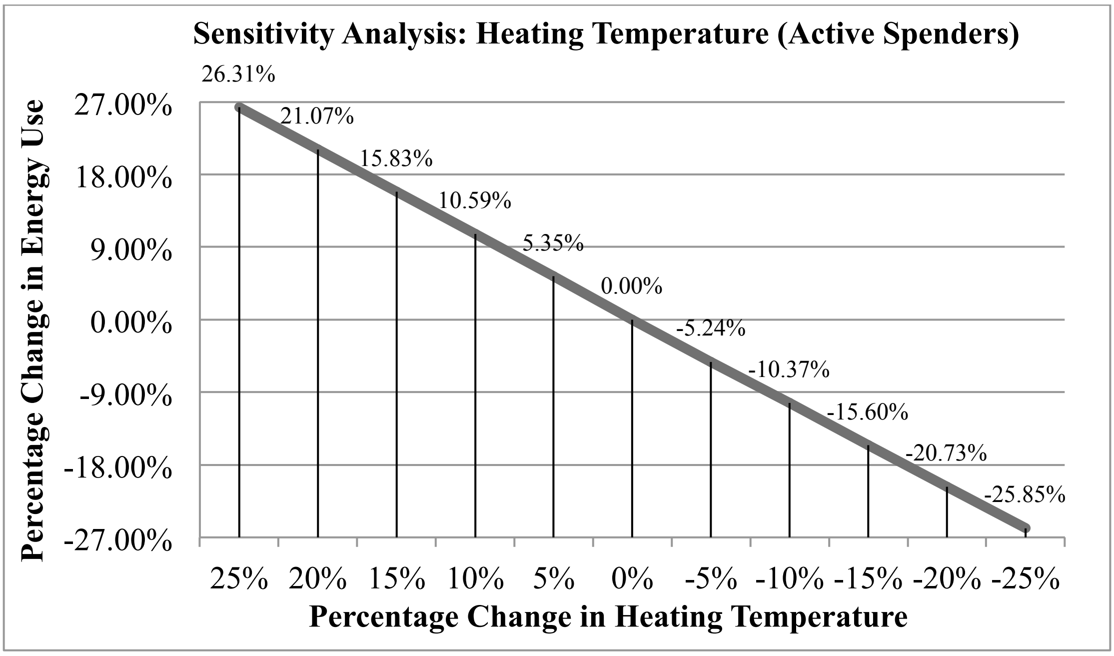


Figure 6.21 Response of energy use to heating temperature change for active spenders
(It shows that 1% increase in heating temperature can lead to around 1.4% to 1.6% increase in energy use for active spenders)

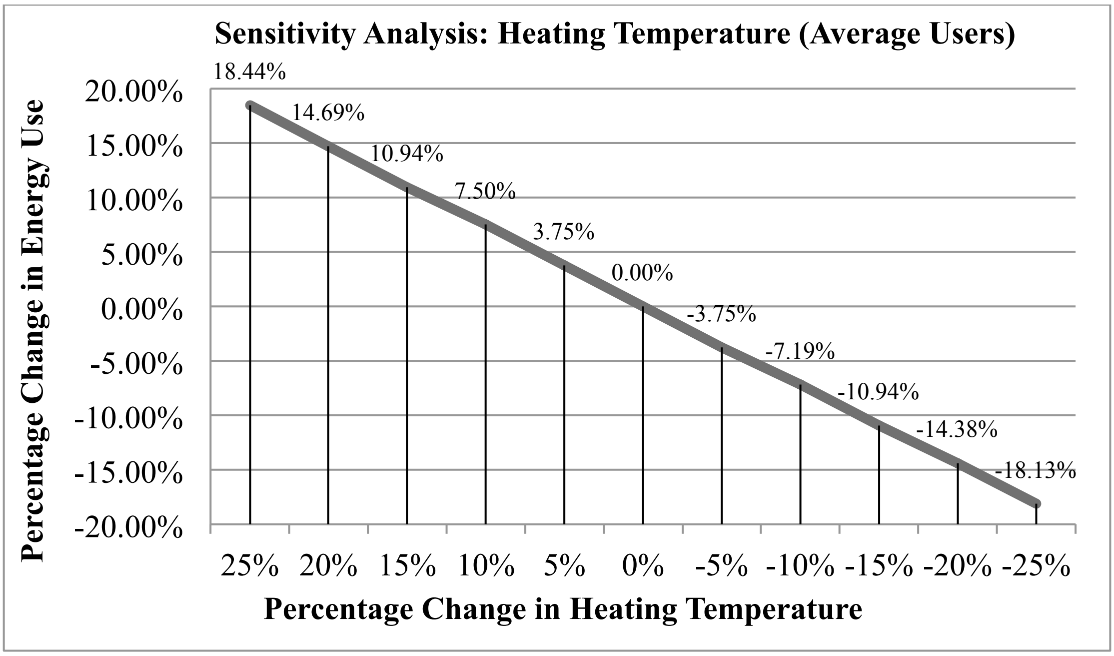


Figure 6.22 Response of energy use to heating temperature change for average users (It shows that 1% increase in heating temperature can lead to around 0.7% to 0.8% increase in energy use for average users)

6.5 Energy and Cost Implications

This section assesses the impact of household archetypes (HA) on the effectiveness of domestic retrofit at the urban level. This was illustrated by a comparison between HA and EPC in terms of the energy saving potential derived from each. A given sample and case study dwelling were used in the analysis to exemplify the importance of incorporating household archetypes in developing retrofit strategies. The use of this approach, and the definition of the average dwelling, served as a convenient proxy for a more detailed assessment and definition of the Cambridge housing stock. Overall, the ambition is to enable a more realistic representation of retrofit saving potentials and to generalise the research outcomes nationwide.

Initially, a base case derived from the mid-terraced house (Figure 6.1e and 6.1f) was selected to test the difference in the efficacy of optimal retrofit options guided by HA and EPC, respectively. According to Cambridgeshire Insight (2008), terraced house was the most common dwelling type, while mid-terraced house was the most representative dwelling type from the Phase II survey. In addition, the average usable floor space in private sector is 91m^2 and 86m^2 in social sector (Cambridgeshire Insight, 2008). Therefore, the medium-sized mid-terraced house was chosen and defined as Cambridge's representative dwelling, forming the base case.

The survey sample and percentage of each type of household is listed in Table 6.4. The aggregated energy saving following various retrofits for each HA was compared with the retrofit saving using the EPC method does not distinguish between household behaviours. After determining the estimated cost of each measure (Table 6.5), the retrofit options were compared and ranked according to their energy saving per pound spent (Figure 6.23 to 6.25). Consequently, eight retrofit levels were formulated based on the number of retrofit options included. The first level had only one and the most cost-effective measure, while the eighth level included all the measures. This was based on the rationale that households would invest in more cost effective measures first, however many they could afford. Here it was assumed that the cost and energy savings were the only factors in influencing households' choices of taking up retrofit measures. The Tariff Comparison Rate (TCR) was introduced to calculate the monetary saving potentials resulting from home energy demand reduction.

The results with respect to the cost-effectiveness of retrofit showed that the optimal ranking of measures varied for each household archetype (Figure 6.23). Despite the fact that tanks and pipes insulation came out on top while window insulation ranked bottom across all household archetypes, all the other measures had somewhat different rankings depending on the archetype. For example, smart meters and controls remained the second most cost effective option for active spenders, conscious occupiers and average users, but dropped to third and fifth for conservers and inactive users respectively. Similarly, heating system upgrade was the second best choice for conservers and inactive users, whereas it dropped to third, fourth and sixth for average users, conscious occupiers and active spenders. All other measures related to building fabric insulation changed little in their rankings among different household types. For instance, ceiling insulation, wall insulation and floor insulation remained third or fourth, fourth or fifth, sixth or seventh, respectively, among all users. Additionally, loft insulation ranked fifth for active spenders, but dropped to sixth or seventh for the other household types. In spite of the variation in their rankings, all the measures were much more cost effective for households with a higher initial energy use, such as the active spenders and conscious occupiers (Figure 6.24 and 6.25). In other words, households like active spenders would achieve a much higher return on retrofit investment compared with inactive users.

The HA method was demonstrated to have a significant impact on energy and cost savings from retrofit (Table 6.6). At both dwelling and city levels, considerably more savings were achieved from using the HA method compared with that from EPC at most retrofit levels. In particular, the HA method could bring additional savings of over 5 to 10 million pounds per year at city scale with all retrofit levels except I and III. While a smaller gap of about £0.7 million was found at retrofit level I, a negative difference occurred at retrofit level III suggesting more savings came from the EPC method when retrofitting with only the first three measures. Furthermore, on average a dwelling was able to make about an extra £120 to £220 in annual savings at all retrofit levels except I and III when guided by HA compared with EPC (Figure 6.26). The savings gap was especially prominent at retrofit level II and VI to VIII. Overall, it was shown that using HA to guide the uptake of energy efficiency measures would significantly improve the retrofit saving potential.

Table 6.4 Proportion of each household archetype based on the survey sample

Household Archetype (HA)	Number	Percentage
Active spender	6	8%
Conscious occupier	11	14%
Average user	26	34%
Conserver	10	13%
Inactive user	24	31%

Table 6.5 Cost estimates and description of retrofit measures

Retrofit measure	Cost *	Description
Smart meters & controls	£700	'Genius Kit' base system £249 + adding 5 zones (£59 per radiator valve + £34 per room sensors)
Internal solid wall insulation	£3,500	The lowest estimate; costs may be significantly more depending on level of work required
Heating system upgrade	£4,000	Replacing an existing boiler in the same location £2,000; Replacing 10 radiators at £200 each *(one per room)
Tanks & pipes insulation	£35	Hot water tank top up insulation (25 to 80 mm) DIY £15; Primary pipe insulation DIY £20
Floor insulation	£950	Lowest estimate; Costs may vary significantly depending

		on level of work required
Window insulation	£3,000	Standard UPVC double glazing costs about £300 per window *10 windows
Ceiling insulation	£280	100mm glass fibre insulation quilt laid over joists or above suspended ceiling grid 6 - 7 (£/m^2)
Loft insulation	£300	Insulation level 270 mm (10.5 inches)

* The estimates are derived from published web sources such as Energy Saving Trust and other professional channels

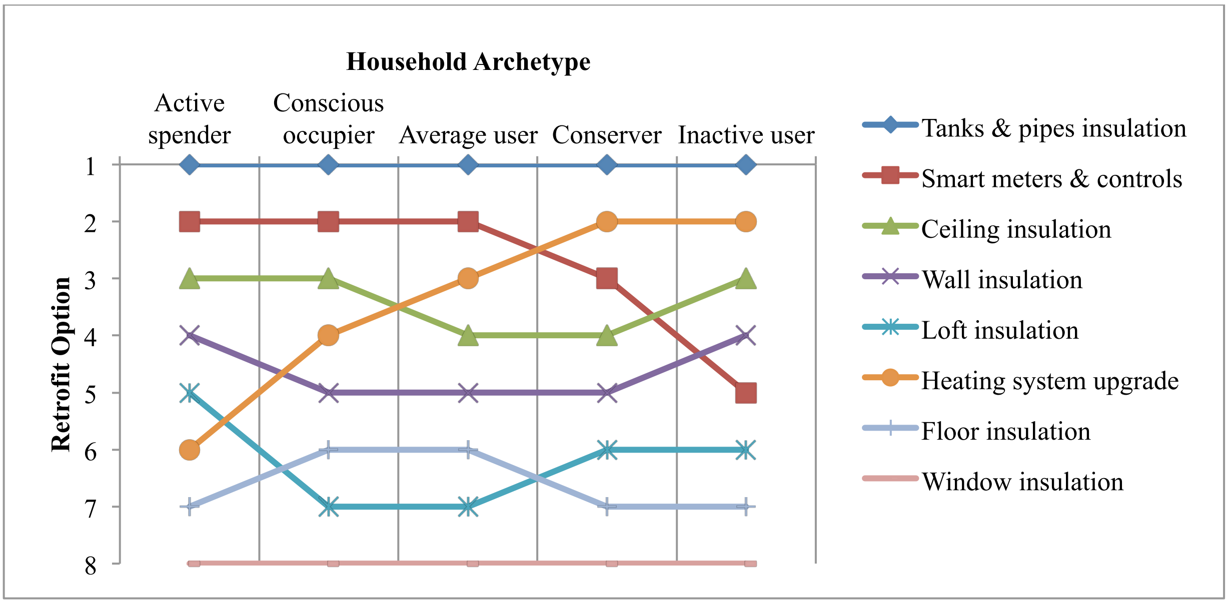


Figure 6.23 Ranking of single retrofit options according to energy saving per pound (kWh/m^2/year/£) across five household archetypes

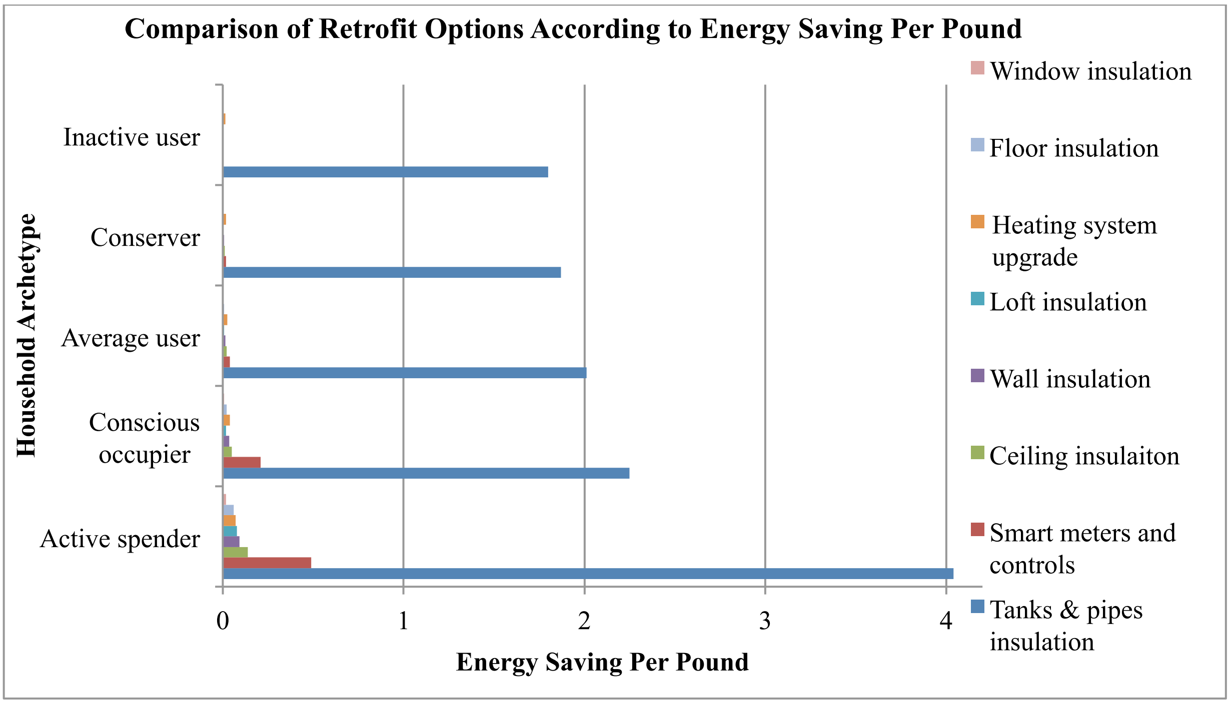


Figure 6.24 Comparison of single retrofit options according to energy saving per pound (kWh/m^2/year/£) in the case study dwelling

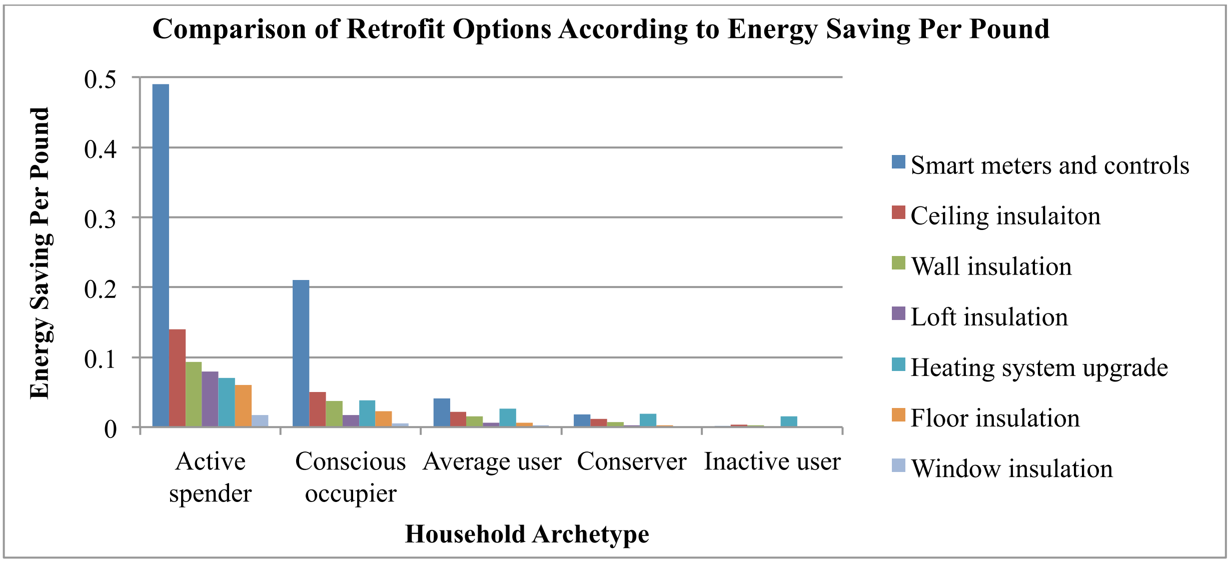


Figure 6.25 Comparison of single retrofit options (excluding tanks and pipes insulation) according to energy saving per pound (kWh/m^2/year/£) in the case study dwelling

Table 6.6 Energy and cost implication of using HA to guide retrofits in comparison with EPC

Retrofit level	EPC saving (kWh/m^2/yr)	HA saving (kWh/m^2/yr)	Difference per dwelling (kWh/m^2/yr)	Difference at dwelling level (£/yr)	Difference at city level (£/yr) **

					*	
I	1st option	70.2	74.2	4.0	14.4	697,970.8
II	1st +2nd options	99.2	160.5	61.3	219.3	10,658,499.4
III	1stto3rd options	203.7	202.9	- 0.8	- 2.8	-134,278.1
IV	1stto4th options	209.9	255.2	45.3	162.0	7,875,100.0
V	1stto5th options	263.6	297.2	33.6	120.3	5,844,319.8
VI	1stto 6th options	269.7	324.9	55.2	197.7	9,608,116.0
VII	1stto 7th options	271.5	331.5	60.0	214.7	10,432,011.7
VIII	1stto 8th options	279.1	341.3	62.2	222.6	10,818,653.0

* Tariff Comparison Rate (TCR): 3.60p per kWh

** Cambridge household number: 48600 (2012 census)

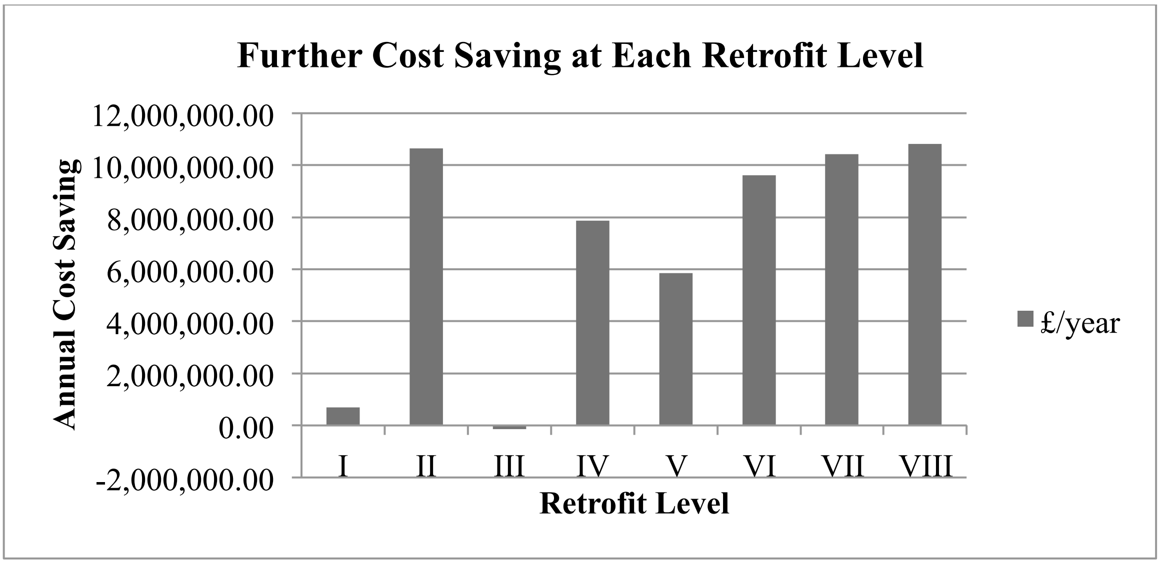


Figure 6.26 Extra cost saving potential from eight retrofit levels at the urban level when incorporating household archetypes, benchmarked against Energy Performance Certificates (EPC)

6.6 Summary

This chapter has illustrated the significance of incorporating household archetypes into any retrofit strategy. Compared with EPC, choosing retrofit measures tailored to each household archetype can considerably improve the energy saving potential, which may result in over 10 million pounds cost saving annually at the urban level, if we assume that the typical dwelling is representative of the potential savings achievable across all dwelling types in Cambridge. On the dwelling level, an average household may save over £220 per year on top of the saving estimated from EPC.

The modelling prediction has shown that the performance of energy efficiency measures may vary significantly and these variations can be distinguished by the use of household archetypes. As shown above, retrofit options affect each archetype differently regarding energy saving, where the level of impact positively corresponds to the initial energy consumption. Despite their variance, building system improvements, particularly heating system upgrades, are the most effective retrofit options across all archetypes, followed by internal solid wall insulation.

With respect to cost-effectiveness, insulation of tanks and pipes triumphed across all archetypes whereas window insulation ranked at the bottom. In spite of this commonality, the optimal ranking of the rest of the measures differs depending on the household archetype. By distinguishing between household groups, each household can work out the most favourable and affordable retrofit strategy. The prediction of the retrofit saving potential can also be improved in light of variations of behavioural patterns by incorporating household archetypes.

CHAPTER 7 DISCUSSION

7.1 Introduction

Based on the research findings from the previous three chapters, this chapter interprets and describes the significance of the results to help address the under-realisation of domestic retrofit. It also discusses policy implications, acknowledges limitations, and provides recommendations for further research. Using a mixed-methods approach, this research investigated the effectiveness of domestic retrofit strategies by incorporating occupant behaviour and comfort. It firstly presented comfort practices through four structural elements: meaning, composition, task and material, showing how retrofit was part of whole bundles of practices of comfort and consumption. Then it postulated five household archetypes: active spenders, conscious occupiers, average users, conservers and inactive users. Finally, modelling results showed that a differentiated approach to retrofit using household archetypes could bring significantly more savings compared with the conventional method employed in EPCs. Overall, the research findings demonstrated that the incorporation of household archetypes in retrofit strategies would achieve much higher effectiveness compared with the standardised approach.

7.2 Occupant Comfort Practices

Using a social practice theory approach, the initial exploratory study showed the interrelations between four structural elements (Figure 7.1), viewing retrofit as part of whole bundles of practices of comfort and consumption. The element of ‘meaning’ refers to the individuals’ subjective and distinctive views on what comfort means, which has implications for how they occupy their homes. ‘Composition’ denotes the idea that people who live together can influence each other’s behaviour, including how they practise comfort and use energy. ‘Task’ represents occupants’ daily schedules, such as cooking or showering, which influence how people use their homes and subsequent energy consumption. ‘Material’ provides a medium between energy and comfort practices.

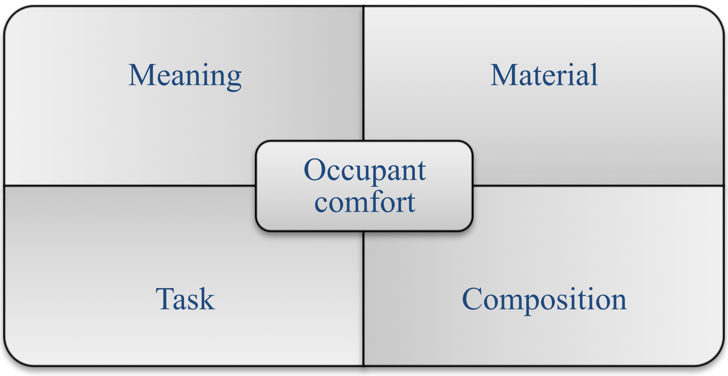


Figure 7.1 Elements of the underlying social practices of occupant comfort

Occupants commonly use energy in the pursuit of comfort, such as heating a house. The way people used energy differed drastically, which was in part to do with their diverse comfort preferences and lifestyles. For example, some occupants preferred a relatively moderate temperature such as 19^{o}C, whereas others were happier with a much higher average room temperature. Even within one household, this contrast could happen, such as the husband putting on a jumper while the wife turns up the heating. This finding is in line with an adaptive comfort model, which shows that people experience the world differently and create their own comfort preferences (de Dear and Brager, 2001; Nicol and Humphreys, 2002). In addition, Chappells and Shove (2005) asserted that comfort is a highly negotiable socio-cultural construct, supporting the view of diversity and variety in people's comfort expectations.

This study further found that excessive energy use was due to technological malfunctions, household rules, personal attitude and knowledge. For example, several households had inoperative heating controls where they were unable to turn down or off the heating, leading to the only option of opening windows to cool down rooms. In some severe cases, the occupant's comfort satisfaction was even compromised by such wasteful energy consumption. Since their rental included heating bills, they weren't too bothered with these technical faults. In addition, some households had their heating on when not occupying the room or house, due to a fixed central setting or a lack of attention to such an issue. Some of them felt less satisfied about their comfort as a result, especially being somewhat cold or too hot at times. Interestingly, there were tenants who had functional thermostats but perceived a lack of control over heating due to their insufficient knowledge about the setting of thermostats.

Prevailing studies tended to frame occupants as the main responsible party for energy saving deficits (Stern, 1985; Sorrell, 2007; Sunikka-Blank and Galvin, 2012; Gram-Hanssen et al., 2012), whereas the results here showed that unnecessary energy demand was primarily caused by technical issues or underdeveloped regulations, in addition to occupants' negligence or ignorance. This means that tackling the under-realisation of retrofit requires a holistic approach that brings behavioural, social and technical aspects together.

The findings provided a framework for evaluating opportunities to reduce home energy demand while maintaining occupant comfort. In particular, the framework suggested four interrelated elements to tackle wasting energy in accordance with occupant comfort preferences. In other words, comfort is highly subjective; diversified behaviour needs to be accommodated at the same time as tackling excessive use and technical inefficiency. Further variables linked to these four elements may help determine specific strategies, such as the characteristics of households and dwellings, as well as occupant behavioural patterns.

7.3 Household Archetypes

Phase II of this study has identified five different household archetypes to serve as a basis for targeted policy interventions tailored to specific socio-demographic groups for domestic energy demand reduction. These are: 1) active spenders; 2) conscious occupiers; 3) average users; 4) conservers and 5) inactive users. Each of these archetypes contains specific behavioural patterns correlated with certain household characteristics based on statistical analyses of empirical data. As a basis for determining behavioural patterns, five factors underlying occupant behaviour variables were found: 1) main space heating; 2) auxiliary space use; 3) main space use; 4) auxiliary space heating and 5) use of appliances. Statistical pattern analysis dichotomising the component scores of the five factors was used to determine the five behavioural patterns. In particular, binary strings obtained after dichotomisation were then grouped according to their overall scores as very high, high, medium, low and very low. Meanwhile, significant correlations were found between the behavioural factors and energy use, household and dwelling characteristics. These correlations contributed to the profiles of the archetypes.

Despite the different clustering bases or criteria that other studies employed, some household archetypes identified in this thesis share similarities with the findings of previous research. For instance, the ‘spenders’ and ‘conservers’ described by Raaij and Venhallen (1983) correspond, to some extent, to the ‘active spenders’ and ‘conservers’ identified in this paper. In both cases, the ‘spenders’ are ‘more often at home’ and ‘more energy consuming’, whereas the ‘conservers’ have a ‘small household size’ and are ‘less energy consuming’. Furthermore, the ‘spenders’ identified by Guerra-Santin (2011) and the ‘active spenders’ have similar characteristics, such as ‘use of more space’, ‘more hours of heating’, ‘large household’ and ‘high income’. The ‘lavish lifestyles’, ‘thrifty values’, ‘practical considerations’ and ‘modern living’ described by Hughes and Moreno (2013) also correspond to the ‘active spenders’, ‘conservers’, ‘conscious occupiers’ and ‘inactive users’ respectively in terms of occupancy, socio-economic status, household composition and energy use.

Different energy efficiency strategies and policy programmes may be appropriate for each of the distinct archetypes. For active spenders, behavioural recommendations (incentives and opportunities) for cutting down their use of heating and appliances may be the best strategy, alongside tailored retrofit measures such as boiler and control upgrades for those with a low heating system efficiency. In contrast, the inactive users are likely to have little scope for behavioural improvement but a limited amount of energy saving might be gained from a mixture of retrofit and behavioural change such as fabric insulation and reducing heating temperatures. Such a balance of behavioural and physical strategies would also benefit average users. On the other hand, retrofit might be the main energy-saving strategy for the conscious occupiers who have a relatively desirable energy behaviour that should be reinforced. Similarly, retrofit could be made affordable through government subsidies to allow conservers to improve their energy-inefficient dwellings. When applying an archetype-based approach to target household energy efficiency, a survey of household and dwelling characteristics as well as behavioural patterns can be used to determine which archetype a given household belongs to.

7.4 Retrofit Strategies

The final phase of the research presented in Chapter 6 illustrated that the performance and ranking of energy efficiency measures varied significantly, with these variations distinguished by the use of household archetypes. In other words, the effectiveness of retrofit options for each archetype varied, but their effects tending to be larger in more energy-intensive households. The results demonstrated a need to prioritise retrofit measures differently to provide maximum benefit to each archetype in terms of energy saving. This challenges the prevailing methods used for generating retrofit recommendations and programmes that use standardised occupant behaviour, such as Energy Performance Certificates (EPC) and Energy Saving Trust. Compared with EPCs, choosing retrofit measures tailored to each household archetype can considerably improve the energy saving potential, which perhaps save over £10 million more per year at the urban level.

Furthermore, targeting higher energy consuming households can bring larger energy savings, especially with building system upgrades and external wall insulation. This is in line with the findings of Wei et al. (2017) that the energy saving potential of all retrofit measures was increased significantly for active heating users compared with that for passive heating users. Dodoo et al. (2017) also asserted that indoor air temperature had a significant impact on the simulated building energy performance and energy efficiency measures. To the contrary, Marshall et al. (2016) suggested the savings from some energy efficiency measures were similar for all three occupancy patterns. These measures included roof, wall and combined insulation, boiler upgrade and temperature reductions. This contrast could be due to the differences in how the user groups were defined and distinguished in each study, such as by different levels of energy consumption. Thus, knowing how to distinguish between household groups so as to determine that each group has the same optimal retrofit options, is crucial for developing retrofit recommendations.

Despite the need for distinguishing among household types, retrofit measures such as tank and pipe insulation remained the top option for cost effectiveness irrespective of variations in behaviour or dwelling type. Other measures such as building system upgrades, particularly heating system upgrades, were the most favourable retrofit options regarding energy saving potential amongst all archetypes, followed by external wall insulation. Window insulation remained the least cost-effective measure across all archetypes. This contradicts with the prevalent view of 'fabric-first' (Institute for Sustainability, 2012; Brás, 2017), suggesting that upgrading building systems can be significantly more effective compared with building fabric improvement.

Overall, retrofit design and policies that incorporate the approach of household archetypes can help address the under-realisation of retrofit while maintaining occupant comfort. Such an approach can significantly improve the reliability of retrofit guidance and recommendations. It will not only aid householders in making better-informed decisions on their options for retrofit, but also assist policy-makers in better incentivising a more widespread uptake of retrofit measures.

7.5 Limitations

The limitations of this research lie primarily in the representativeness of the sample. Firstly, the households were not randomly selected from a large population, but rather based on the availability of EPCs and willingness to participate in this study. This might have biased the sample. In addition, the sample was also relatively small and is from Cambridge – a city with a unique socio-geographic location in the UK that is not wholly representative of the wider population. Nevertheless, this research does not aim to be exhaustive in typology terms, but rather to provide indications of different ways of reducing energy use by targeting different household groups. Despite the relative small sample size, factor analysis was viable given high communities scores, a relatively small number of expected factors and a low model error (Preacher and MacCallum, 2002).

In addition, self-reported data obtained from questionnaires and interviews relied on what people said and could rarely be independently verified. This was especially the case for the survey that was carried out without triangulation, and hence could have introduced bias that might undermine the results. Even with triangulation in the initial exploratory study, there were mismatches between what the occupants said and the measurement of heating settings during the initial in-depth case studies. Discrepancies like this could be caused by participants' cognitive biases such as memory biases, attribution, exaggeration and social desirability bias. Due to the nature of human uncertainty and complexity, self-reported data were taken at face value to represent an approximate estimations. Since the emphasis was on the development of the modelling approach incorporating estimations, the outcome remains valid despite the uncertainty around human subjects. Furthermore, the derivation of hourly profiles have been intuited for the purpose of testing the research hypothesis, that the presentation of different profiles is more important than their absolute precision, and this in a way is more to do with identifying and understanding qualitative differences of household social practices. Despite the limitations in this approach, the overall objective was met through testing different scenarios and speculating on their relative impacts.

The use of building energy modelling to test various retrofit measures and scenarios of household archetypes also had its limitations. In particular, theoretical scenarios and simplified parameters used in the modelling may lead to calculations that deviate from what the energy performances and savings would be in reality. For example, any interactive effects between the measures were not considered, and neither were renewable and low carbon technologies linked to energy supply. Moreover, airtightness and draught proofing were not selected as retrofit measures due to limitations in the functions available in IES-VE to adjust infiltration rates resulting from building leakage or other unintentional openings in the modelled dwelling. Finally, the sensitivity of each parameter was subject to the physical conditions of the base case, such as the cavity wall area ratio, single glazed window area ratio, and the number of windows and doors where draught proofing for infiltration was needed. These fixed conditions will have an effect on the overall sensitivity of each parameter tested, which may lead to different results compared to other studies (e.g. Murray and O'Sullivan, 2012). Nevertheless, it provides a general indication of the potential range of impact from these retrofit measures on energy use.

The scope of this research was limited to a cross-sectional evaluation of variations in occupant comfort and behavioural patterns rather than a longitudinal one. In other words, there were assumptions that occupant comfort preferences and behavioural patterns remained relatively constant over time within each distinct household archetype. However, possibilities arise regarding any rebound effect or comfort take-back as a result of the implementation of energy efficiency measures. Such considerations can result in changes of retrofit energy savings, leading to deviations from the initial prediction. A possible route to tackle this problem is to estimate how behavioural patterns might change, such as from one household archetype to another. Thus the design considerations can once again incorporate household archetypes to estimate the potential optimal strategies for achieving the maximum energy saving potential in the long run. Here the use of household archetypes will connect to the life cycle of the dwellings, such as estimations of how the occupants might change and the duration of each archetype.

7.6 Summary

This research demonstrated the significance of incorporating occupant behaviour and comfort criteria in energy retrofit design and policy. It showed how comfort practices are diversified, and the need to support such variations of practices when developing retrofit strategies. It developed a modelling approach that incorporates household archetypes to improve retrofit design. This approach significantly increases the retrofit saving potential at the urban scale and helps address the under-realisation of retrofit.

Overall, the findings suggest a tailored approach to retrofit improves energy saving prediction and subsequent reliability. In particular, using household archetypes as a method to represent variations of households helps target different groups of households more effectively. Methodologically, it provides a framework for the development of retrofit design and programmes, underpinned by a socio-technical perspective. The research thus contributes to the sustainable development of the built environment and shows a practical way to tackling the needed reduction in carbon emissions.

CHAPTER 8 CONCLUSIONS

8.1 Research Summary

In the context of the UK government's goal of reducing carbon emissions to combat climate change, this research has demonstrated the significance of improving retrofit design and policy by incorporating occupant behaviour and comfort, which help address the under-realisation of domestic retrofit. One of the main contributing factors to the retrofit shortfalls is occupant behaviour. For example, building energy modelling often uses standardised assumptions about a set of comfort conditions. This excludes the social and behavioural dimensions of comfort. From a social science perspective, comfort has been approached with qualitative studies, separated from a technical scientific approach. This research has gauged the gap between qualitative methods of understanding occupants and quantitative analyses of building performance modelling. It has developed household archetypes based on the underlying social practices pertaining to occupant comfort. It has used a sequential exploratory investigation to uncover the varying effectiveness and optimal rankings of retrofit measures according to distinct household archetypes. It has shown that retrofit strategies designed using a modelling approach that incorporates household archetypes can significantly increase energy savings at urban scale while maintaining occupant comfort levels.

Overall, this research has achieved its aim and objectives as well as provided answers to the three questions set out in the beginning through three sequential phases. Phase I provided answers to the question on how occupants carried out social practices of comfort at home. It analysed occupant social practices using four interrelated structural elements, including meaning, material, task and composition. It showed how retrofit as part of material infrastructure is deeply embedded in the bundle of practices, and that different household practices may lead to different optimal retrofit options. Phase II answered the question about what the household archetypes were. It derived household archetypes through a survey and statistical analyses of the survey data. The analyses included factor analysis which obtained five factors underlying household behaviours, followed by statistical pattern analysis that generated five behavioural patterns as well as non-parametric correlation analysis that established the links between behavioural patterns, dwelling and social-demographic characteristics, leading to the identification of the five household archetypes. Phase III answered the question regarding the extent to which household variations had an impact on the effectiveness of retrofit measures. It demonstrated that retrofit using a tailored approach incorporating household archetypes could bring significantly higher savings compared with the conventional method used for EPCs. It used IES-VE modelling simulation to test various scenarios created based on the five household archetypes. The outcome confirmed that a differentiated approach to retrofit using household archetypes could improve the effectiveness of domestic retrofit.

8.2 Contribution to Knowledge

The purpose of this research is to improve the reliability of retrofit recommendations by addressing the performance gap concerning the standardised assumptions about indoor comfort conditions and occupant behaviour. The findings have highlighted the importance of a tailored approach to retrofit, considering not only the dwelling characteristics, but also the way occupants live in their homes. Very little research has examined behavioural influences on the varying effectiveness and optimal rankings of retrofit strategies. A number of studies have produced household archetypes, while none has linked these to the variations in optimal retrofit strategies. This research has shown the diversity in occupants' social practices of comfort in the setting of Cambridge, UK. It has developed the structural elements holding together occupants' comfort practices, namely meaning, composition, task and material. From this qualitative understanding of household variations and relevant parameters contributing to such variations, it has generated insight about the way to categorise different groups of households.

The research has developed five distinct household archetypes for informing a tailored retrofit decision-making process. These archetypes are: active spenders, conscious occupiers, average users, conservers and inactive users. The use of household archetypes represents a step forward in bridging the performance gap while informing a practical solution to enhancing retrofit guidance. By considering behavioural and dwelling variations in estimating retrofit effectiveness, both the ranking and energy saving potential of single retrofit measures can be improved significantly. This contradicts conventional retrofit approaches differentiating only between the physical characteristics of the dwelling, thereby allowing different retrofit measures to be prioritised in response to variations of household archetypes for better retrofit decision-making. Without this prioritisation, home energy efficiency may not be optimised cost-effectively and households could be misled about payback periods. Therefore, a tailored approach to retrofit using household archetypes will bring significantly higher energy savings compared with existing methods such as Standard Assessment Procedure.

Additionally, the research has shown that improving building systems brings far larger energy savings compared with building fabric. This contradicts the prevalent view on the fabric-first approach. An overall emphasis on building system upgrades, such as tank and pipe insulation, heating system upgrade, smart meters and controls can help reduce energy demand more effectively, particularly for active spenders, conscious occupiers and average users. Even though external wall insulation was amongst the most effective measures, measures to insulate the rest of the building envelope, however, had relatively little impact, especially window insulation.

As one of the few studies evaluating behavioural impact on retrofit strategies, this research provides support for targeting specific household types concerning which retrofit measures are most effective. The differentiation by household types is vital for energy policy and retrofit programmes to achieve optimum outcomes. Defining five distinct household archetypes improves existing user segmentations by linking behavioural factors with household and dwelling characteristics, as well as energy use. This allows policy interventions to be geared towards identifiable groups of households to maximise their impact and effectiveness. It also provides a framework to incorporate occupant behaviour and comfort in developing retrofit strategies. By considering household practices with bottom up approaches, we can identify the optimal intervention for each household group. This will enable the development of tailored, effective policy and energy efficiency strategies.

8.3 Recommendations

Based on the research results, courses of action are proposed to address the retrofit performance gap in practice. While there are many factors contributing to the performance gap, the recommendations focus on the area of occupant behaviour and comfort. More specifically, the proposed guidance concerns representing diversity in behavioural patterns and comfort practices for retrofit strategies, rather than the possible longitudinal changes resulting from lifestyle change or other reasons. In fact, apart from smart meters and controls, other retrofit measures might incur unplanned behavioural change, such as the rebound effect or comfort take-back. However, due to the deep-rooted uncertainty associated with such longitudinal changes, retrofit design may consider these unplanned changes based on certain assumptions, for example, potential changes from one household archetype to another.

While current official retrofit guidance offers a one-size-fits-all view on the effectiveness of energy efficiency measures irrespective of occupant behaviour, this research suggests tailoring the information to distinct household types is crucial. Including a variety of estimation in retrofit savings linked to each household type in retrofit guidance can enable homeowners and relevant stakeholders to plan retrofit better and anticipate more realistic savings. An interactive web interface can provide a viable solution to provide the public with tailored information. Such an interactive interface already exists, such as Home Energy Check, regarding the dwelling characteristics for users to search for their specific retrofit suggestions. An inclusion of behavioural and comfort choices in this interface will significantly improve the accuracy and usefulness of retrofit recommendations.

Energy Performance Certificates (EPC) can also benefit from including behavioural and comfort information to improve the reliability of their retrofit recommendations. For example, affixing a set of questions addressing household behaviours and comfort preferences in EPCs can help occupants decide which household type they belong to. Subsequently this will enable them to understand the differences in retrofit options based on their household type. The information obtained on households can further help relevant agencies target specific household groups more effectively, using tailored messages and measures.

Retrofit design programmes can also ran household surveys to decide the best strategy to improve the energy efficiency of the buildings or for a community. Differentiating household groups will not only allow a better energy saving prediction, but will also help decide on the most effective retrofit measures to achieve an optimum energy demand reduction. Such use of distinct household types can also apply to low energy building design. We envisage that emphasising a tailored approach to retrofit by employing a representative set of household archetypes allow achieve a better reduction in domestic energy demand for a more sustainable housing sector.

8.4 Further Research

Realising the energy saving potential of building retrofit is an ongoing global challenge, and one of the key steps is to make more accurate predictions. By developing more efficient, effective, robust and reliable prediction models, the outcome will support decision-making in designing more effective retrofit strategies. While complete audits are costly and time consuming, uncertainty arises as to how building and behavioural characteristics influence energy use. Therefore, further research should look into efficient ways of producing reliable retrofit recommendations, which address such uncertainty especially related to occupant behaviour. For example, future research could develop an assessment tool including a set of simplified but essential questions regarding occupant behaviour and dwelling characteristics. The approach can be designed with better predicting power linked with user and behaviour profiles to identify tailored retrofit strategy for each household. By obtaining such input information, this tool can help produce tailored, cost-effective improvement recommendations and more reliable energy saving estimates for both users and retrofit stakeholders.

Another area for examination is how occupant behaviour might change over time especially after implementation of retrofit measures. This could help further tackle the energy performance gap regarding a potential rebound effect or comfort take-back. The outcome from this will allow more realistic expectations of retrofit savings, as well as assist the development of energy efficiency policies and technologies. From a policy perspective, knowing what motivates or triggers occupants to change their behaviours may help develop interventions targeting such changes. For example, regulations requiring tenants to pay heating bills separately may become a financial incentive, which encourages occupants to use heating more sparingly. From an engineering perspective, further research can support the design of retrofit technologies that incorporate social and behavioural factors. For example, user research and usability testing can help develop technologies encouraging less energy use, such as smart control systems.

On a broader level, further research can expand to include both supply and demand side interventions for effective carbon emissions reduction. For example, retrofit measures could include not only various insulations and building system upgrades, but also a set of renewable energy technologies. Together with a deeper understanding of energy demand characteristics, further research should investigate different future scenarios as to how household archetypes and comfort practices impact the integrative design of domestic energy systems.

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APPENDIX A Instruments for Phase I Data Collection

A.1 Consent Form

UNIVERSITY OF CAMBRIDGE

CONSENT FORM

Research Title: Energy Efficiency and Comfort Practices: Interactions Between Building Technologies and Occupant Behaviour
Researcher: Hui Ben
Department: Architecture

Please initial box

1. I confirm that I have read and have understood the information sheet dated [02 Dec 2013] for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason, without my rights being affected. ☐

3. I understand that, under the Data Protection Act, I can at any time ask for access to the information I provide and I can also request the destruction of that information if I wish. ☐

4. I agree to take part in the above study. ☐

The contact details are:

Mobile: 07565486893
E-mail: hb403@cam.ac.uk
Address: **Department of Architecture**
University of Cambridge
1-5 Scroope Terrace
Cambridge
CB2 1PX

A.2 Information Sheet

UNIVERSITY OF CAMBRIDGE

INFORMATION SHEET

Research Title: Energy Efficiency and Comfort Practices: Interactions Between Building Technologies and Occupant Behaviour
Researcher: Hui Ben

You are being invited to participate in a research study. Before you decide whether to participate, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and feel free to ask us if you would like more information or if there is anything that you do not understand. We would like to stress that you do not have to accept this invitation and should only agree on take part if you want to.

Thank you for reading this!

The research aim is to increase both energy saving and occupants' comfort through developing building design solutions, systems, technologies and interfaces that can assist users in developing an energy conscious behaviour together with a comfortable and healthy indoor environment.

This survey collects occupancy data for evaluating household comfort experiences. Besides the information sheet, you should also receive a copy of a questionnaire survey form and a daily activity logbook. If you are willing to have a face-to-face interview session with us to discuss further the issues relating to this research study, please contact us. The dairy/logbook involved takes approximately 30 minutes in total to fill in everyday for a week, and the semi-structured interview would take about 1 to 2 hours. Please provide us with your name, contact number and best time to contact you (in the last section of the questionnaire survey form attached) so that we can contact you again. Please note that we will never pass your details onto a third party. We need to make it clear that there is no intended reimbursement or benefit (at the time of your participation or in the future) if you take part in this study. However, your participation will be of benefit to others particularly the architects, planners, local authorities, government and more importantly the occupants.

Please note that your participation is voluntary and that you are free to withdraw prior to the time without giving any reason and without your rights being affected. Under the Data Protection Act, you can at any time ask for access to the information you provide and you can also request the destruction of that information if you wish.

If you are unhappy, or if there is a problem, please feel free to let us know by contacting us at the mobile or email address stated below and we will try to help. If you have a complaint which you feel you cannot come to us, then you should contact the Humanities and Social

Sciences Research Ethics Committee, School of the Humanities and Social Sciences, 17 Mill Lane, Cambridge CB2 1RX (cshssethics@admin.cam.ac.uk). When contacting the Research Ethics Committee, please provide details of the name or description of the study (so that it can be identified), the researcher involved, and the details of the complaint you wish to make.

The data collected will be stored securely and it will be depersonalized, and your information will be entirely anonymous. The data collected will be used for this research study only and will be stored until the end of this research study that is targeted on 30th Sep 2017. All data will be disposed of towards the end of the study. If the results are to be published, you will not be identifiable from the results unless you have consented to being so.

Please do not hesitate to contact us (Hui Ben—PhD researcher in the Department of Architecture, University of Cambridge) if you need further clarification. You may reach us at phone number 01223 332989 (best time to contact is from 9am to 5pm during the weekday) or email address hb403@cam.ac.uk.

With Thanks!

A.3 Semi-structured Interview

UNIVERSITY OF CAMBRIDGE

SEMI-STRUCTURED INTERVIEW

How do you like your house?

What do you like to do in an ordinary day?

Which room do you spend the most time in?

What are your hobbies?

How long do you sleep in an ordinary day?

When do you usually turn the heating on?

What is your setting for heating system in an ordinary day?

When do you open windows?

How long do you usually leave the window open?

What do you do when you first wake up in the morning?

What does your perfect day look like?

Aside from food, water, and shelter, what one thing could you not live a day without?

When do you usually turn on the lighting?

How do you like the lighting at home?

How do you like to improve your home in general?

If you were given choices, would you like intelligent control at home (i.e. heating system, windows, lighting, cooking, etc)?

Do you like spending time at home or out?

A.4 Questionnaire

UNIVERSITY OF CAMBRIDGE

QUESTIONNAIRE SURVEY

You will be asked a set of questions in this survey. This involves questions to be answered in your own words and view. It is very important that you answer as accurately as you can, take your time, and consult records if you want.

SECTION 1: GENERAL

1. How long have you lived in this house?
2. Ownership? A. Privately owned; B. Private Rented; C. Social Rented.
3. Maintenance? A. Self-maintained; B. Landlord; C. Housekeeper/Technical stuff.
4. Energy bill: A. Pay by consumption; B. Pay by floor area; C. Included in rental; D. Other to be specified.
5. Household info:

- Number of person in your home:

The following info includes all household members:

- Age (s):
- Gender (s):
- Marital status (es):
- Ethnic group (s):
- Economic activities: A. Employee (full time); B. Employee (part time); C. Self-employed; D. Unemployed; E. Full-time student; F. Retired; G. Looking after home/family; H. Permanently sick/disabled; I. Other
- Occupation (s):

SECTION 2: HOUSE

1. How many rooms do you have? And what are they?

2. Which of the items do you have at home? (Window blinds or shades, Operable window, Thermostat, Portable heater, Permanent heater, Portable fan, Adjustable air vent in wall or ceiling (1 with mechanic fan in kitchen, 1 passive in bedroom), Adjustable air vent in floor, Door to interior space, Door to exterior space, Electronic equipment/appliances, Lights, Other items to be specified)
3. How do you usually use the items chosen above? (i.e. when and for how long)
4. What building technologies have been installed in your home? (i.e. Lighting sensor, HVAC and/or controls system improvements, No-cost/low-cost or behavioural improvements, Energy-supply and/or peak-demand management, Building-envelope improvements, On-site renewable energy, Smart-grid or smart-building technology, Other to be specified)

SECTION 3: COMFORT

1. How do you define comfort? What is the most important aspect?
2. What do you do to feel comfortable?

SECTION 4: SATISFACTION

Below are statements that may describe your comfort. Seven numbers are provided for each question; please circle the number you think most closely matches your feeling. Relate these questions to your comfort at the moment you are answering the questions.

Below is an example:

	Filling out this questionnaire about my comfort	Very Dissatisfied				Very Satisfied		
		1	2	3	4	5	6	7
1	Thermal comfort	1	2	3	4	5	6	7
2	Heating length	1	2	3	4	5	6	7
3	Heating temperature	1	2	3	4	5	6	7
4	Clothing level	1	2	3	4	5	6	7
5	Level of control over thermal condition	1	2	3	4	5	6	7
6	Indoor air quality	1	2	3	4	5	6	7
7	Air velocity	1	2	3	4	5	6	7
8	Humidity	1	2	3	4	5	6	7
9	Extent to which you can control the ventilation	1	2	3	4	5	6	7
10	Ability to adjust window openings	1	2	3	4	5	6	7

11	Visual comfort	1	2	3	4	5	6	7
12	Amount of artificial lighting	1	2	3	4	5	6	7
13	Amount of daylight	1	2	3	4	5	6	7
14	Level of control on artificial lighting	1	2	3	4	5	6	7
15	Level of control on daylight	1	2	3	4	5	6	7
16	Acoustic comfort	1	2	3	4	5	6	7
17	Sound privacy	1	2	3	4	5	6	7
18	Level of noise	1	2	3	4	5	6	7
19	Ability to reduce transmitted sound	1	2	3	4	5	6	7
20	Level of control over acoustic conditions	1	2	3	4	5	6	7
21	Cleanliness and maintenance	1	2	3	4	5	6	7
22	General living space	1	2	3	4	5	6	7
23	General building design	1	2	3	4	5	6	7

Please give explanations for each choice above.
Any additional comments or recommendations about your personal comfort experiences

A.5 Personal Diary Log

PERSONAL DIARY LOG

Date ………………………

When	Where	What (Activities)	Why (Comments)
00 - 01			
01- 02			
02 - 03			
03 - 04			
04 - 05			
05 - 06			
06 - 07			
07 - 08			
08 - 09			
09 - 10			
10 - 11			
11 - 12			
12 - 13			
13 - 14			
14 - 15			
15 - 16			
16 - 17			
17 - 18			
18 - 19			
19 - 20			
20 - 21			
21 - 22			
22 - 23			
23 - 24			

A.6 Data Logger

Figure A.1 Data loggers located at various corners of monitored rooms

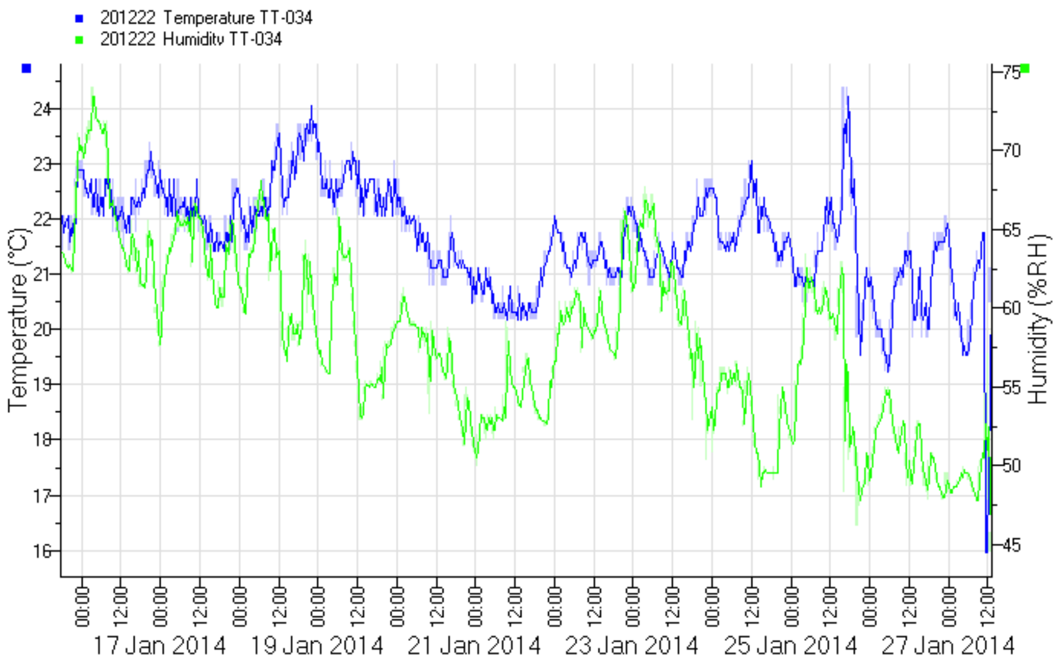


Figure A.2 Sample output from data loggers

A.7 Sample photos

Figure A.3 Sample photos on heating controls

Appendix B Questionnaire for Phase II Data Collection

B.1 Information Letter

UNIVERSITY OF CAMBRIDGE

INFORMATION LETTER

Dear Resident,

You are being invited to participate in an academic research project "*Energy Efficiency and Occupant Comfort in UK Homes*". This project is from Department of Architecture, University of Cambridge. Within this research, we try to evaluate your comfort at home which can provide valuable knowledge for designing strategies to improve your dwelling and life quality. It will be of benefit to others particularly the architects, planners, local authorities, government and more importantly the occupants.

You are invited to participate in a survey. The survey is hosted via online for your convenience, or it can be filled in using the hardcopy enclosed with the prepaid self-addressed envelope. It will take only about 5 minutes to complete. To say thank you for helping us, we will enter you into a prize draw to win a £50 Amazon gift voucher.

Link to survey: http://cambridge.eu.qualtrics.com//SE/?SID=SV_eDrBylx3qdf6ljn

Your answers are completely anonymous and are regulated by the Data Protection Act 1998. All the information and personal details will be treated confidentially and will not be passed onto a third party. During the survey you will be exposed to a set of questions. Please fill out the survey below as honestly and completely as possible.

Please do not hesitate to contact us (Hui Ben—Doctoral Researcher in the Department of Architecture, University of Cambridge, or the Humanities and Social Sciences Research Ethics Committee, School of the Humanities and Social Sciences, 17 Mill Lane, Cambridge CB2 1RX cshssethics@admin.cam.ac.uk) if you need further clarification. You may reach us at phone number 01223 332989 (best time to contact is from 9am to 5pm during the weekday) or email address hb403@cam.ac.uk.

With Thanks!

Department of Architecture
University of Cambridge

B.2 Survey Questionnaire

Questionnaire

Dear Resident,

You are being invited to participate in a research project. This project is from Department of Architecture, University of Cambridge. Within this project, we try to evaluate your comfort at home which can provide valuable knowledge for designing strategies to improve your dwelling and life quality.

You are invited to participate in a survey. Your answers are completely anonymous. All the information and personal details will be treated confidentially. During the survey you will be exposed to a set of questions. Please fill out the survey below as honestly and completely as possible.

My overall satisfaction with the dwelling and its physical condition

	Very Dissatisfied					Very Satisfied
	1	2	3	4	5	6	7

My overall satisfaction with my thermal comfort at home

	Very Dissatisfied					Very Satisfied
	1	2	3	4	5	6	7

How satisfied are you with your thermal comfort in each place at home? (choose rooms that are applicable)

	1	2	3	4	5	6	7
Master Bedroom							
Bedroom							
Guest Room							
Living room							

Dining room						
Kitchen						
Study/Office						
Bathroom/Toilet						
Basement/Storage areas						
Conservatory						
Utility Room						
Hall						
Other(please specify)						

How do you find the temperature in each place at home? (choose rooms that are applicable)

	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold
Master Bedroom	○	○	○	○	○	○	○
Bedroom	○	○	○	○	○	○	○
Guest Room	○	○	○	○	○	○	○
Living room	○	○	○	○	○	○	○
Dining room	○	○	○	○	○	○	○
Kitchen	○	○	○	○	○	○	○
Study/Office	○	○	○	○	○	○	○
Bathroom/Toilet	○	○	○	○	○	○	○
Basement/Storage areas	○	○	○	○	○	○	○
Conservatory	○	○	○	○	○	○	○
Utility Room	○	○	○	○	○	○	○
Hall	○	○	○	○	○	○	○
Other(please specify)	○	○	○	○	○	○	○

What is your clothing level at home?

1 layer ○ 2 layers ○ 3 layers or more ○

My overall satisfaction with my comfort at home

Very Dissatisfied — Very Satisfied

	1	2	3	4	5	6	7

Do you have any comments on your comfort at home?

How many hours of a typical week do you spend at home?

In a typical week, how many hours of your total time at home has been spent on the following activities:

Working (computer based or paper based)	0
Cooking	0
Dining	0
Sleep	0
Personal Hygiene	0
Housework	0
Exercise	0
Social	0
Other (e.g.hobbies, leisure activities) - please specify	0
Total	0

Over the last few months, how many hours of a typical week have the following places been used? (choose rooms that are applicable)

Master Bedroom	0

Bedroom	0
Guest Room	0
Living room	0
Dining room	0
Kitchen	0
Study/Office	0
Bathroom/Toilet	0
Basement/Storage areas	0
Conservatory	0
Utility Room	0
Hall	0
Other(please specify)	0
Total	0

Over the last few months, how many hours of a typical week have the following places been heated? (choose rooms that are applicable)

Master Bedroom	0
Bedroom	0
Guest Room	0
Living room	0
Dining room	0
Kitchen	0
Study/Office	0
Bathroom/Toilet	0
Basement/Storage areas	0
Conservatory	0
Utility Room	0
Hall	0
Other(please specify)	0
Total	0

Have any energy efficient measures been installed to improve your home's performance?

Dwelling age

pre-1919	1919-44	1945-64	1965-80	1981-90	post 1990
○	○	○	○	○	○

Tenure type

Owner occupied	Private rented	Rented from local authorities	Rented from housing association
○	○	○	○

Household type

single	couple	family with children	single with children	extended family	non-family household
○	○	○	○	○	○

Household size

1 person	2 people	3 people	4 people	5 people or above
○	○	○	○	○

What is your age?

Under 15 years	15 to 24 years	25 to 34 years	35 to 44 years	45 to 54 years	55 to 64 years	65 years and over
○	○	○	○	○	○	○

What is the highest level of education you have completed?

Less than High School	High School / GED	Bachelor Degree	Masters Degree	Doctoral Degree	Professional Degree (JD, MD)
○	○	○	○	○	○

Working status

Unemployed	Part-time	Full-time	Retired	Student
○	○	○	○	○

Where are you employed?

- ○ PRIVATE-FOR-PROFIT company, business or individual, for wages, salary or commissions
- ○ PRIVATE-NOT-FOR-PROFIT, tax-exempt, or charitable organization
- ○ GOVERNMENT employee
- ○ SELF-EMPLOYED in own NOT INCORPORATED business, professional practice, or farm

SELF-EMPLOYED in own INCORPORATED business, professional practice, or farm

Working WITHOUT PAY in family business or farm

Please indicate your occupation:

Managers	Professionals	Technicians and associate professionals	Clerical support workers	Service and sales workers	Skilled agricultural, forestry and fishery workers	Craft and related trades workers	Plant and machine operators, and assemblers	Elementary occupations	Armed forces occupations
○	○	○	○	○	○	○	○	○	○

What is your combined annual household income?

Less than £15,000	£15,000 – 19,999	£20,000 – 24,999	£25,000 – 29,999	£30,000 – £49,999	£50,000 or more
○	○	○	○	○	○

How much is your energy bill per year?

Energy Efficiency Rating

	A	B	C	D	E	F	G
Current	○	○	○	○	○	○	○
Potential	○	○	○	○	○	○	○

Environmental Impact (CO_2) Rating

	A	B	C	D	E	F	G
Current	○	○	○	○	○	○	○
Potential	○	○	○	○	○	○	○

Dwelling type

End-terrace house	Mid-terrace house	Semi-detached house	Detached house	Maisonette	Flat
○	○	○	○	○	○

Total floor area (m2)

Estimated energy use, carbon dioxide (CO2) emissions and fuel costs of this home - per year (Current)

0	Energy use (kWh/m2)
0	Carbon dioxide emissions (tonnes)
0	Lighting (£)
0	Heating (£)
0	Hot water (£)

Estimated energy use, carbon dioxide (CO2) emissions and fuel costs of this home - per year (Potential)

0	Energy use (kWh/m2)
0	Carbon dioxide emissions (tonnes)
0	Lighting (£)
0	Heating (£)
0	Hot water (£)

Elements current performance - Energy efficiency

	Very poor	Poor	Average	Good	Very good
Walls - external	○	○	○	○	○
Walls - internal	○	○	○	○	○
Roof - pitched	○	○	○	○	○
Roof - room(s)	○	○	○	○	○
Floor	○	○	○	○	○
Windows	○	○	○	○	○
Main heating	○	○	○	○	○
Main heating controls	○	○	○	○	○
Secondary heating	○	○	○	○	○
Hot water	○	○	○	○	○
Lighting	○	○	○	○	○

Elements current performance - Environmental

	Very poor	Poor	Average	Good	Very good
Walls - external	○	○	○	○	○
Walls - internal	○	○	○	○	○
Roof - pitched	○	○	○	○	○
Roof - room(s)	○	○	○	○	○
Floor	○	○	○	○	○
Windows	○	○	○	○	○

Main heating	○	○	○	○	○
Main heating controls	○	○	○	○	○
Secondary heating	○	○	○	○	○
Hot water	○	○	○	○	○
Lighting	○	○	○	○	○

Dwelling orientation

South	North	East	West	South-East	South-West	North-East	North-West
○	○	○	○	○	○	○	○

Home address

Congratulations, if you made it to the end of this questionnaire! That is quite a feat that you deserve to be applauded for. Thank you for your interest, your valuable time, and for sharing about your comfort experience at home. We hope to see you soon!

B.3 Survey Note

UNIVERSITY OF CAMBRIDGE

Dear Sir or Madam:

You are being invited to participate in a research project. This project is from Department of Architecture, University of Cambridge. Within this project, we try to evaluate your comfort at home which can provide valuable knowledge for designing strategies to improve your dwelling and life quality.

You are invited to participate in a survey, which is web-based and should take less than 10 minutes to complete. Your answers are completely anonymous and are regulated by the Data Protection Act.

Please, participate by using this link:
http://cambridge.eu.qualtrics.com//SE/?SID=SV_eDrBylx3qdf6ljn

Alternatively, we can come back to your home with a hard copy of the survey if the online survey is not filled in.

Thank you!

Department of Architecture
University of Cambridge

Appendix C Phase II Survey Data

This Appendix shows the aggregated data characteristics of the sample collected during the household survey in Phase II (see Chapter 5). Empirical evidence on household behaviour and satisfaction has been collected and presented in six categories (sections C.1 to C.6). These include: 1) time length of personal activities, 2) time length of occupying a space, 3) heating hours of a space, 4) clothing level, 5) rating of overall satisfaction in comfort, thermal comfort and dwelling, 6) rating of thermal comfort and temperature sensation in individual rooms. The relationship among these parameters and energy consumption is shown in C.7. In addition to the data shown here, open-ended questions such as installation of energy efficient measures and comfort have also been discussed and recorded. C.8 includes an overview of the data report from the survey.

C.1 Time Length of Personal Activities

The occupants were asked to report the hours they spent on a set of activities in a typical week. Figure C.1 shows the percentage of each activity with respect to the average values. Figure C.2 shows the min, max and average values of each activity listed above. Figure C.3 to Figure C.11 present the detailed values from all participants in ascending order for each variable/activity. These figures show the composition of each dataset of the activities, which shed light on how the ways people perform activities at home are distributed. Each variable had one or more extreme cases forming the min and max values. In some cases such as working and cooking, it is easily understandable that some occupants may choose not to work or cook at all at home, while some may spend a lot of time on working (e.g. work from home) and/or cooking. In some variables, only one extreme case with max or min value exists, which might have occurred due to an error or special circumstances. For example, one participant reported 60 hours of dining per week, which is far beyond what the other participants described and what is realistic. Another participant reported spending 56 hours per week on housework, stating that it was her job to do so as a stay-in housekeeper. Also, another respondent had 5 hours per week for sleep at the dwelling, as this occupant had another place to stay for the majority of the time.

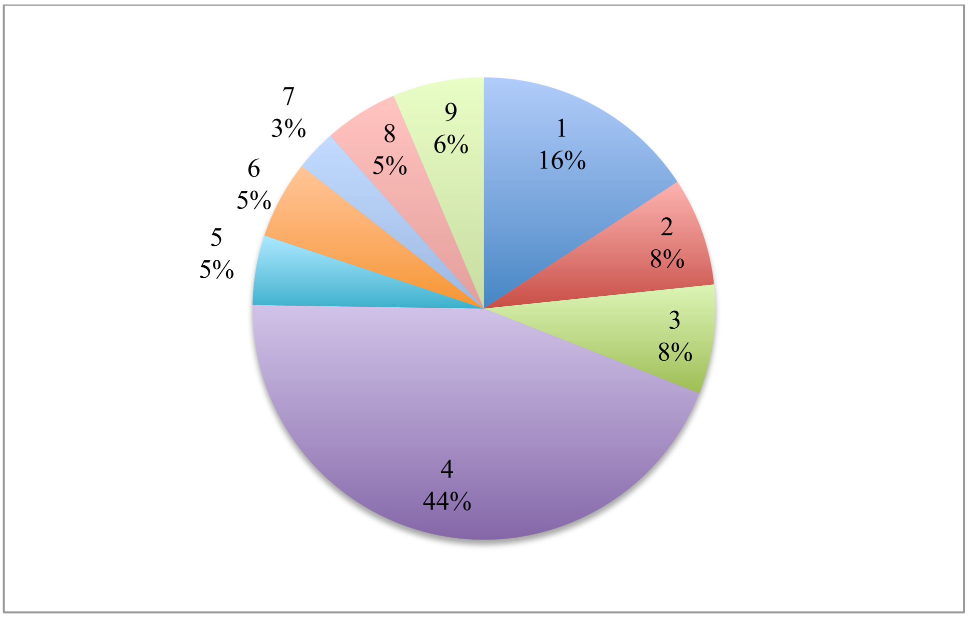


Figure C.1 Hours spent on activities in a typical week - personal activities including nine pre-defined types: 1) working, 2) cooking, 3) dining, 4) sleep, 5) personal hygiene, 6) housework, 7) exercise, 8) social, 9) other.

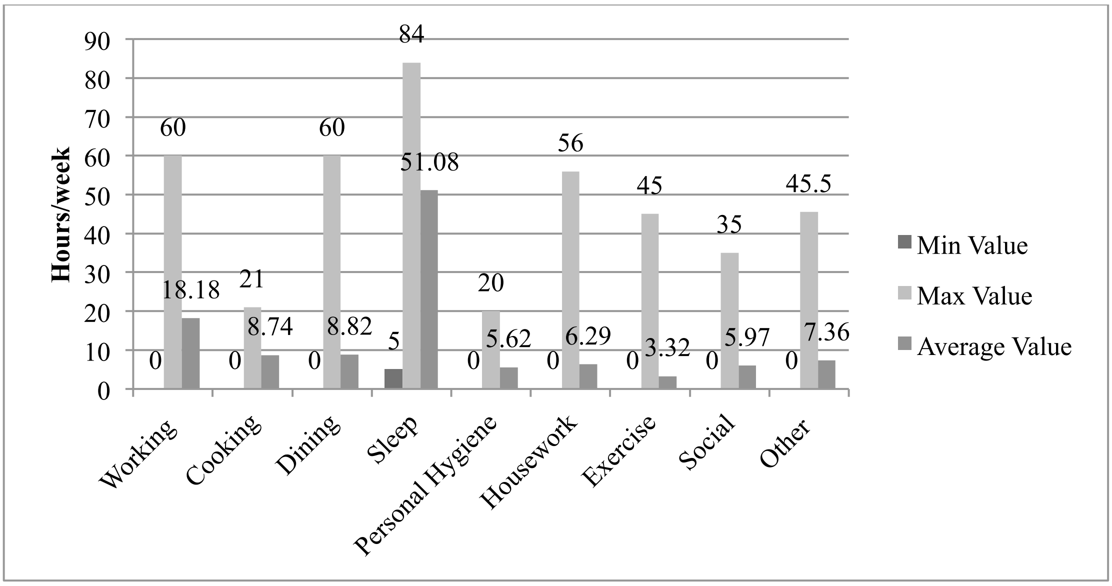


Figure C.2 Hours spent on personal activities in a typical week, with min, max and average values of each activity

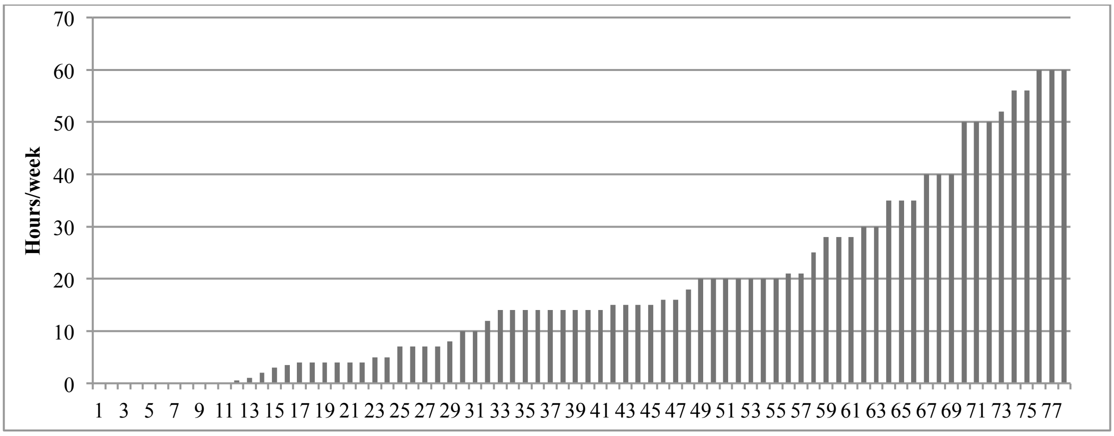


Figure C.3 Hours spent on working at home in a typical week

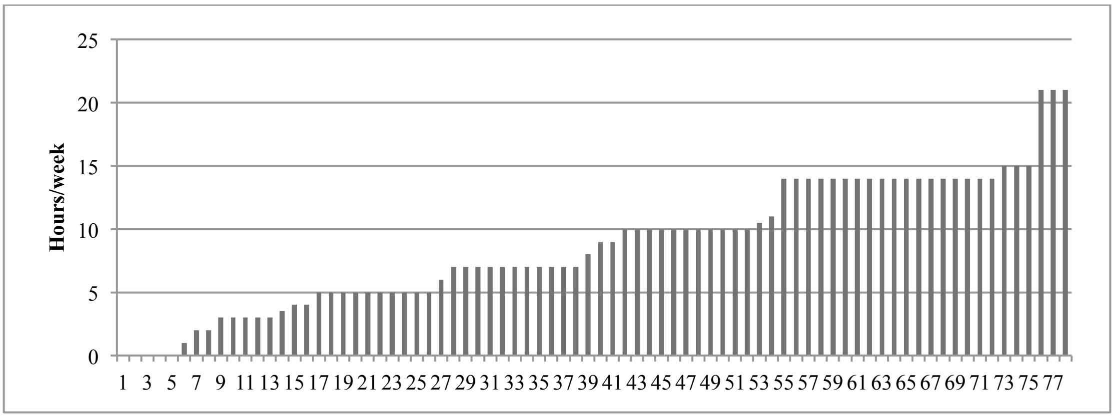


Figure C.4 Hours spent on cooking at home in a typical week

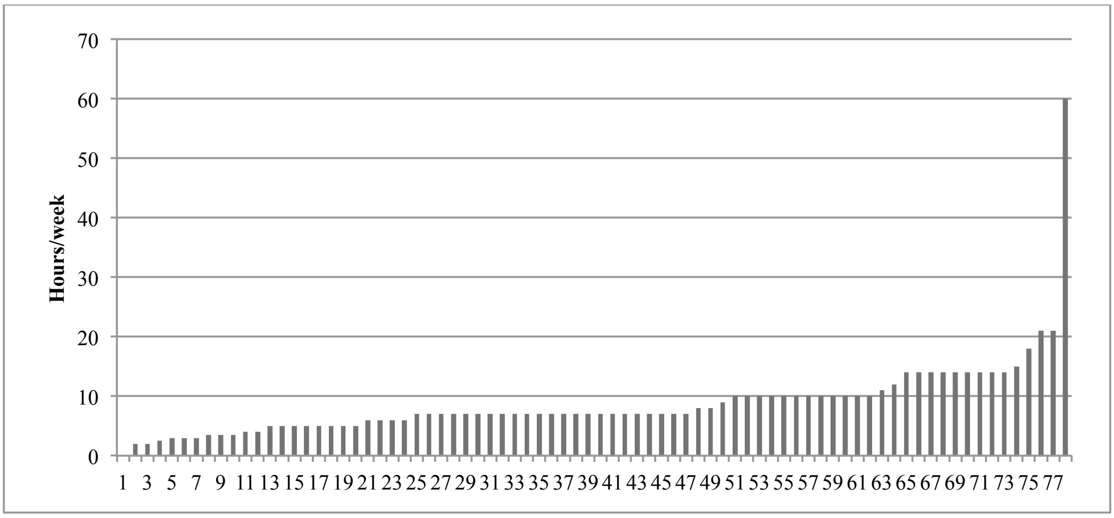


Figure C.5 Hours spent on dining at home in a typical week

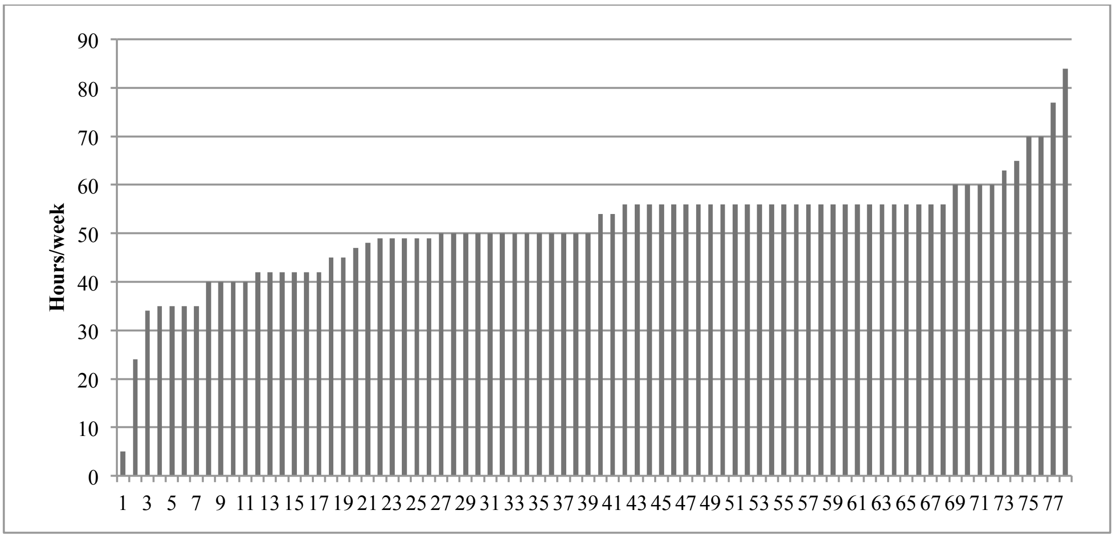


Figure C.6 Hours spent on sleep at home in a typical week

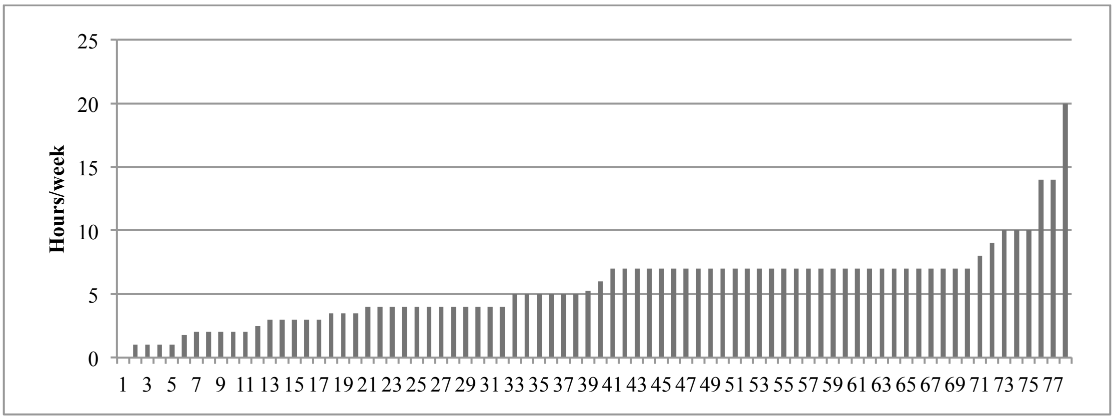


Figure C.7 Hours spent on personal hygiene at home in a typical week

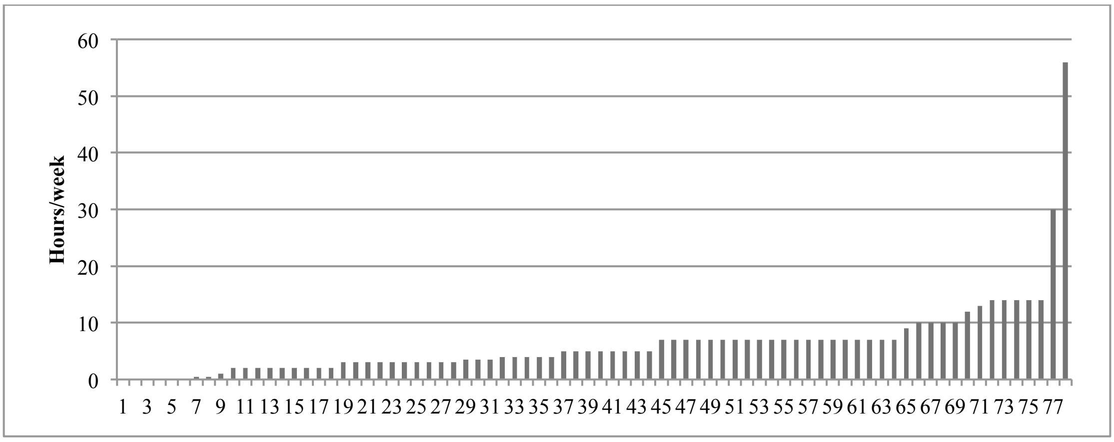


Figure C.8 Hours spent on housework at home in a typical week

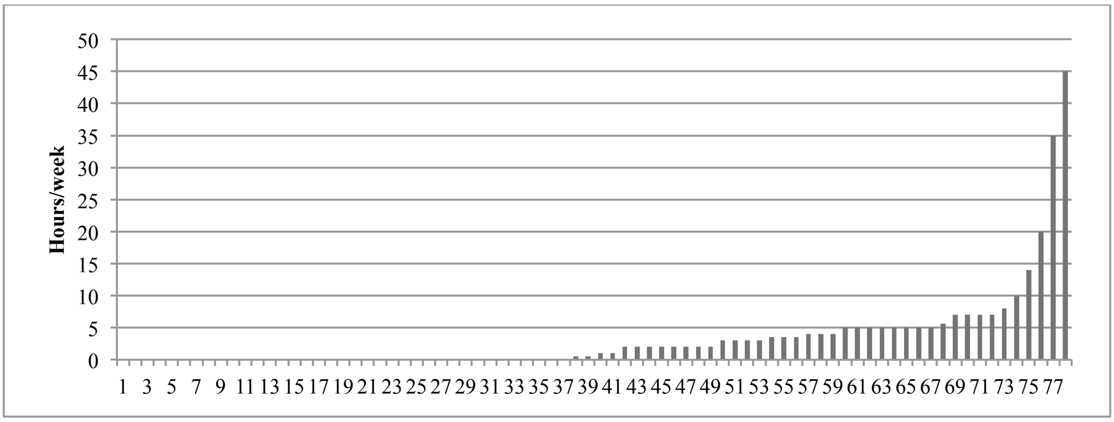


Figure C.9 Hours spent on exercise at home in a typical week

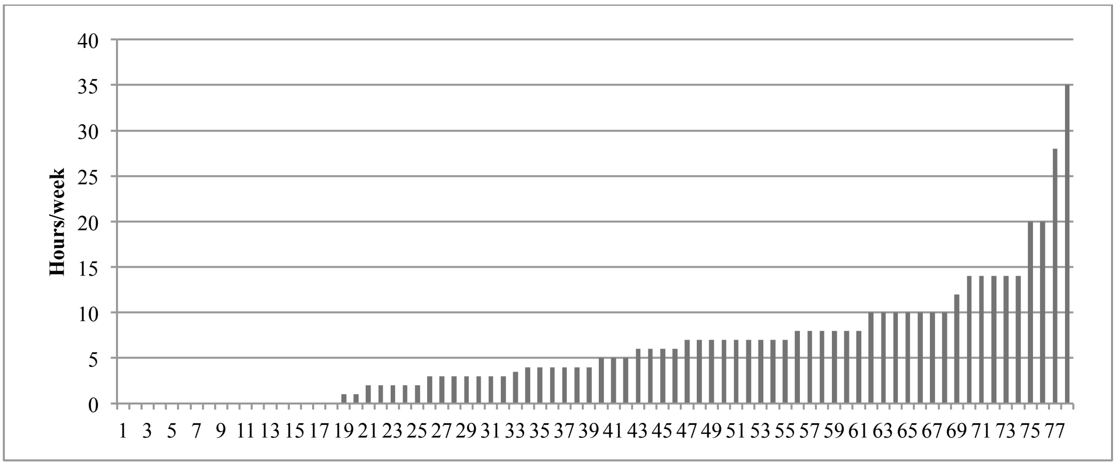


Figure C.10 Hours spent on social activities at home in a typical week

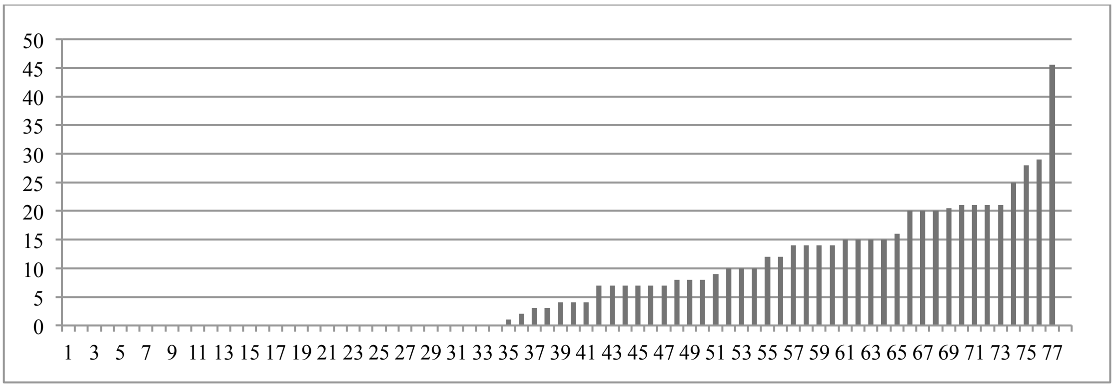


Figure C.11 Hours spent on other activities at home in a typical week

C.2 Space Usage: Time Length of Occupying a Space

Participants reported the hours of usage of individual rooms in their dwellings in a typical week. The list of rooms was derived from the names of parts of a conventional English house: 1) master bedroom, 2) bedroom, 3) guest room, 4) living room, 5) dining room, 6) kitchen, 7) study/office, 8) bathroom/toilet, 9) basement/storage areas, 10) conservatory, 11) utility room, 12) hall, 13) other unspecified room. As shown in Figure C.12, the min, max, and average values of usage hours of each room from all respondents are presented. From the average values shown, master bedroom was used for the longest time (33%), followed by bedroom (24%), living room (20%), kitchen (15%), guest room (12%), dining room (9%), study/office (8%), bathroom/toilet (7%), hall (2%), basement/storage areas (2%), utility room (1%), conservatory (1%), and other unspecified room (0.2%).

The detailed usage hours of individual rooms are presented in ascending order (Figure C.13 to Figure C.25), which sheds light on the ways rooms being occupied are distributed among all participants. Some of these rooms were occupied to various extents by most of the participants, such as master bedroom, living room, kitchen and bathroom/toilet. In contrast, some rooms were only reported with occupying hours by a few respondents, including basement/storage areas, conservatory, utility room, hall and other unspecified room. It is easily understandable that the layouts of the dwellings surveyed were different and the majority of them did not have auxiliary rooms such as a basement or conservatory. A lack of certain rooms listed above within some participants' dwellings contributed to some of the 'zero occupying hours' of these individual rooms. There were a few exceptional cases in the majority of the rooms showing extremely long hours of usage, which may not be acceptable in common sense. For example, one lady stated that she used the hall as the study place as it was warmer than the rest of dwelling. Such unconventional usage of spaces at home show that the rooms were not always used in the way the design intended.

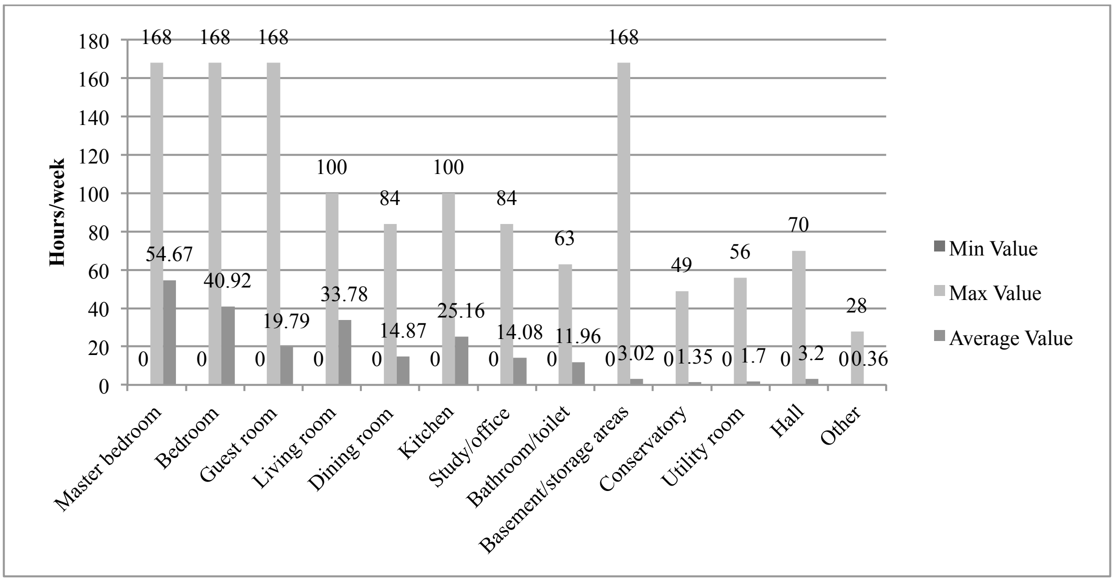


Figure C.12 Hours of usage of individual spaces at home in a typical week

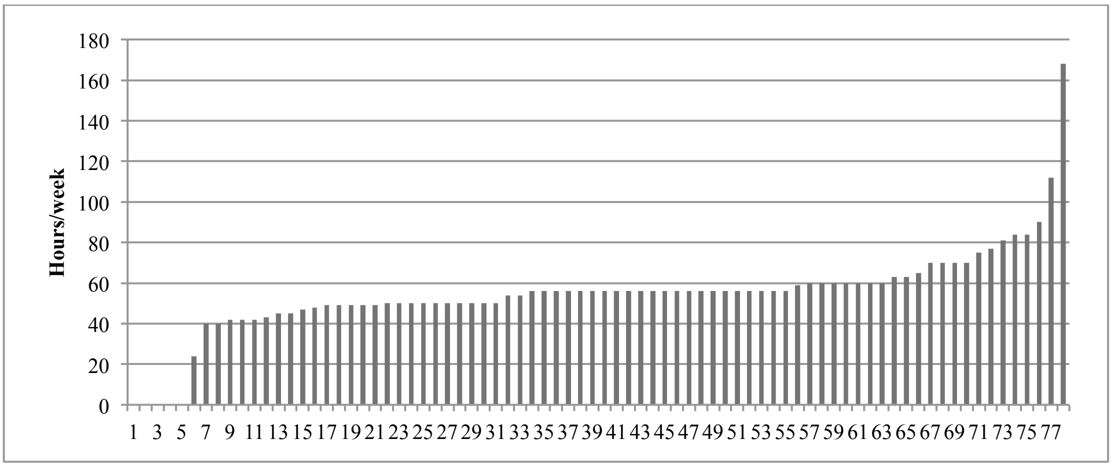


Figure C.13 Hours of usage of master bedroom in a typical week

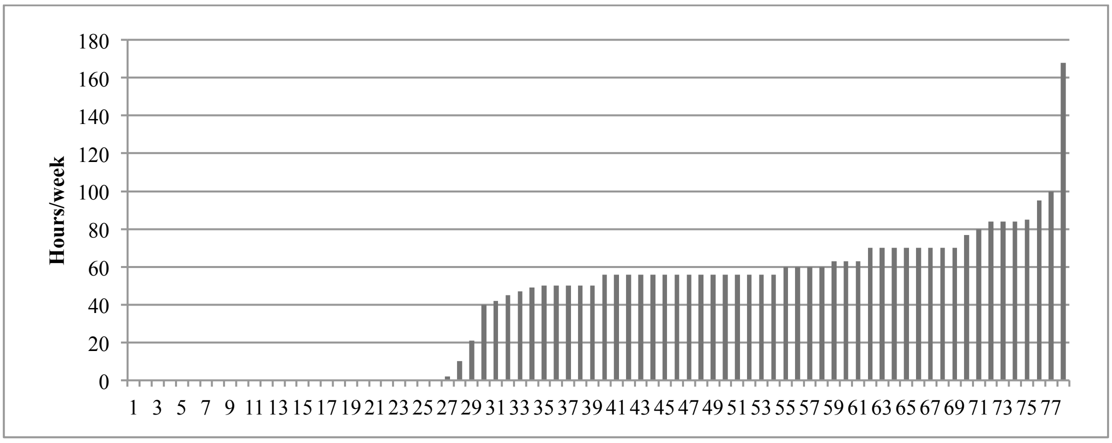


Figure C.14 Hours of usage of bedroom in a typical week

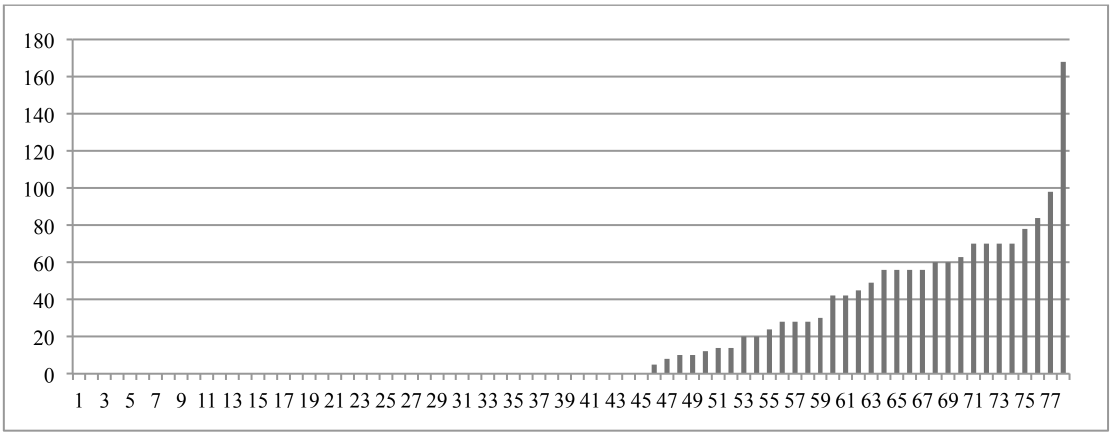


Figure C.15 Hours of usage of guest room in a typical week

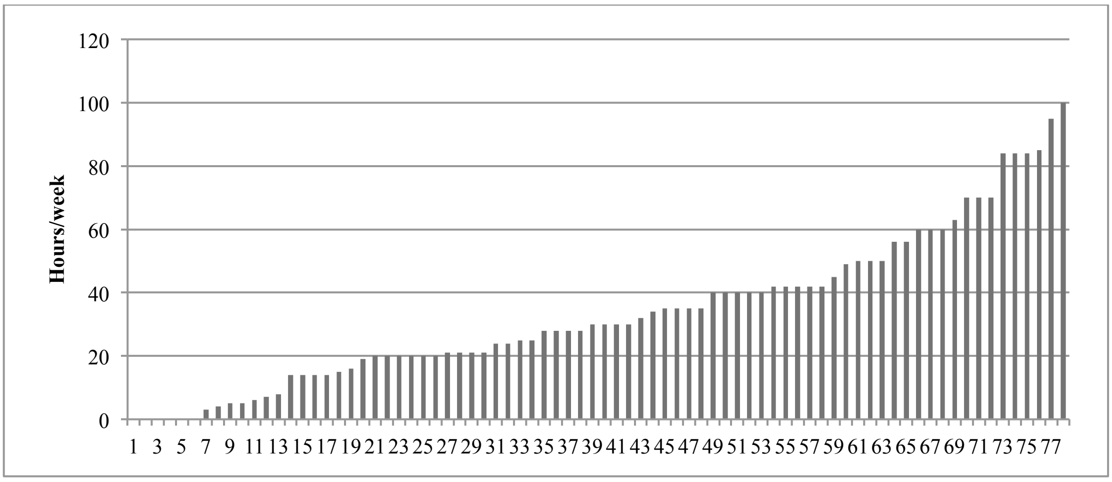


Figure C.16 Hours of usage of living room in a typical week

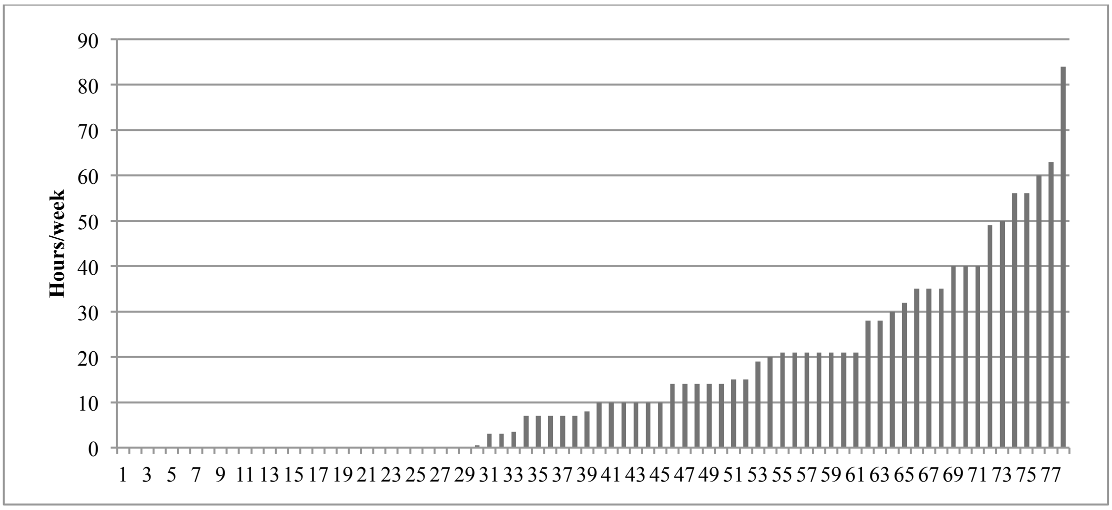


Figure C.17 Hours of usage of dining room in a typical week

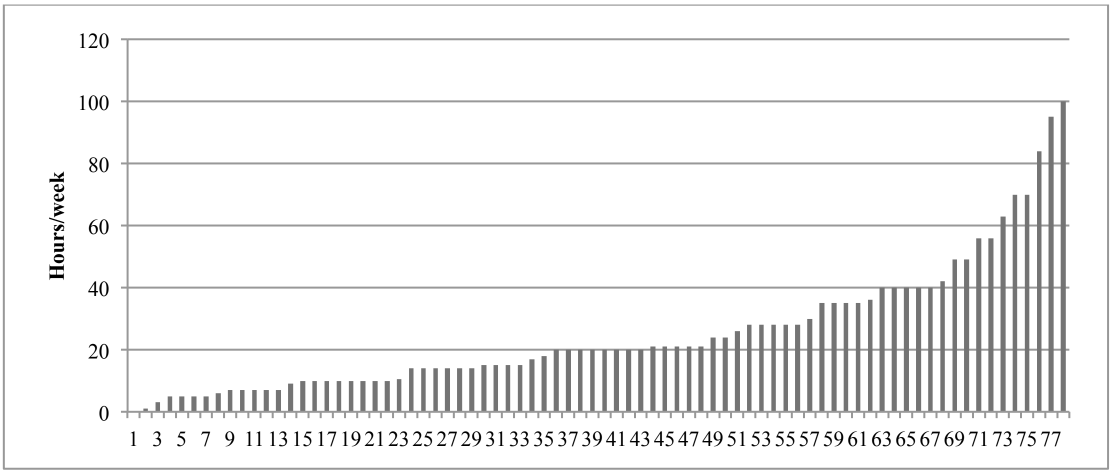


Figure C.18 Hours of usage of kitchen in a typical week

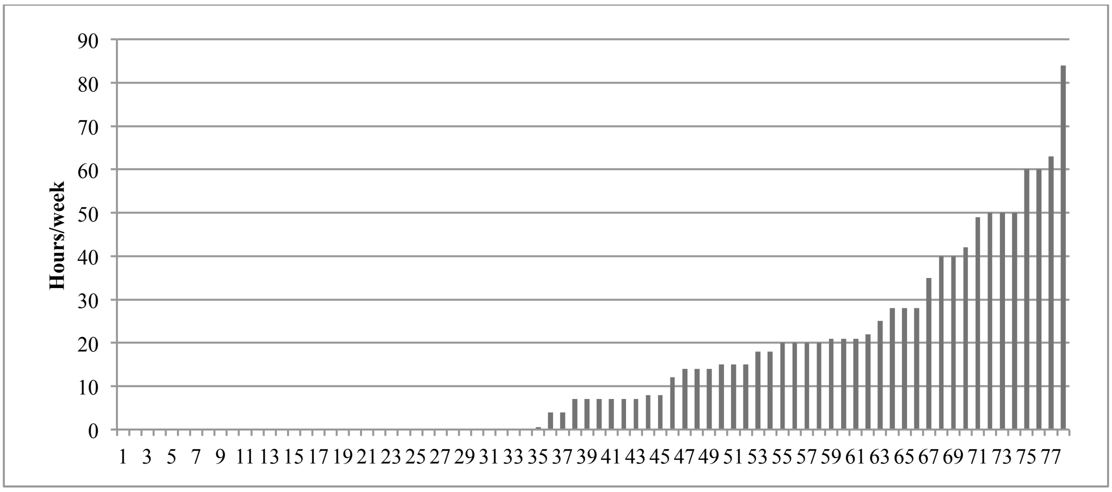


Figure C.19 Hours of usage of study/office in a typical week

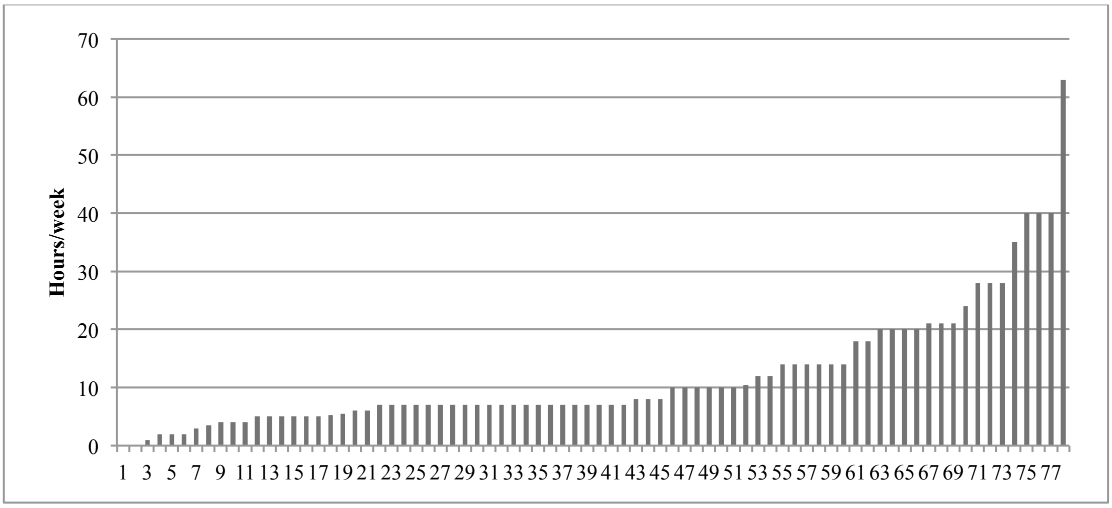


Figure C.20 Hours of usage of bathroom/toilet in a typical week

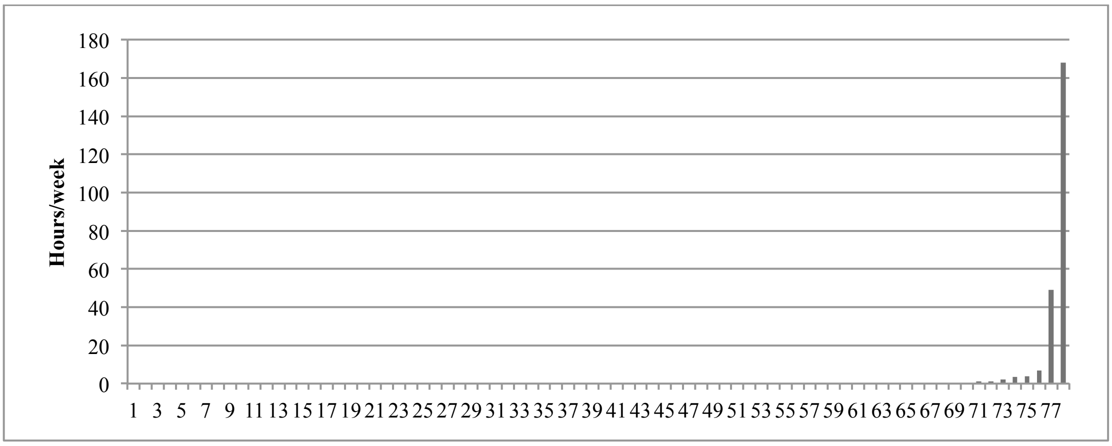


Figure C.21 Hours of usage of basement/storage areas in a typical week

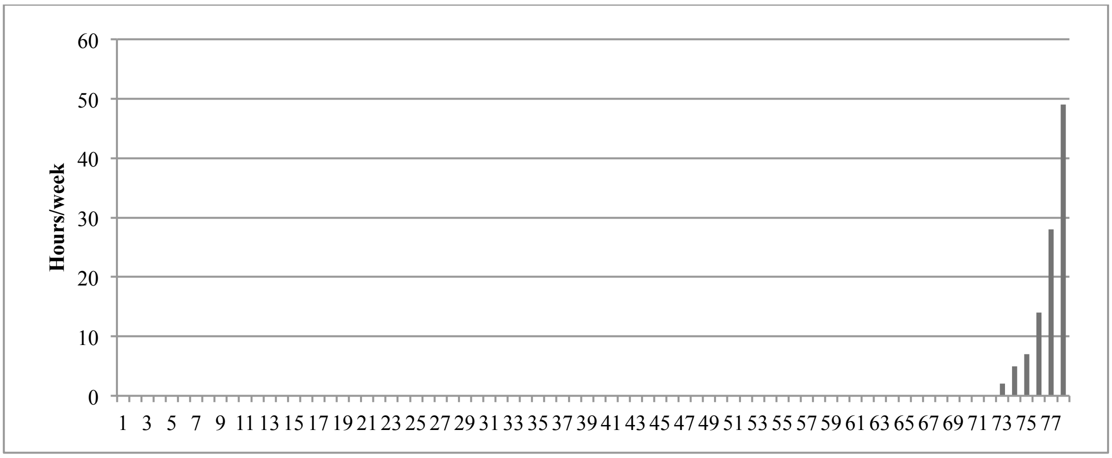


Figure C.22 Hours of usage of conservatory in a typical week

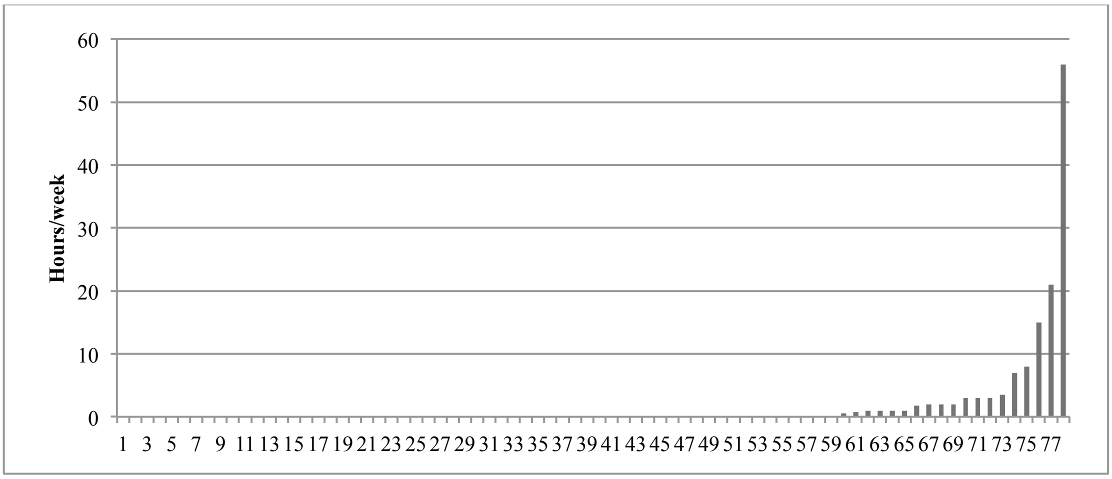


Figure C.23 Hours of usage of utility room in a typical week

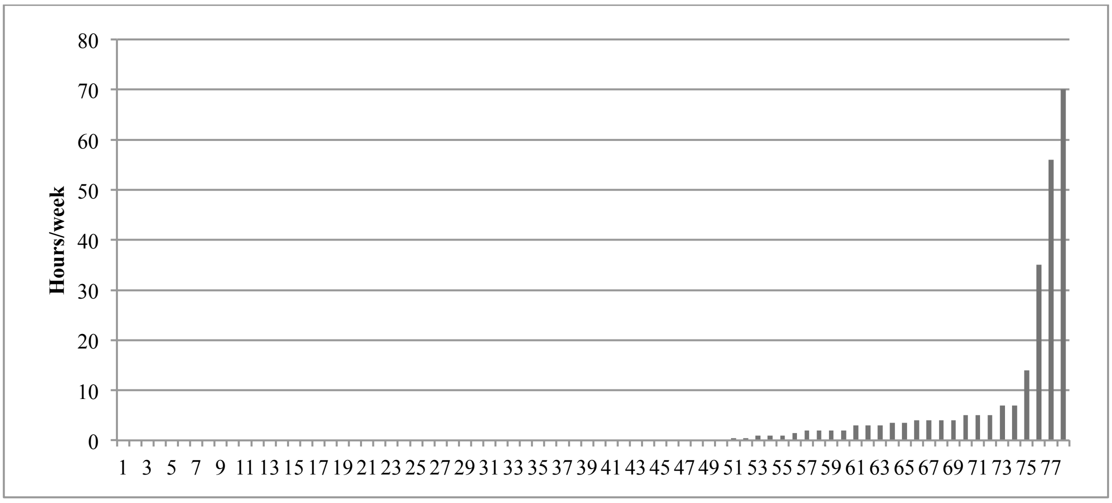


Figure C.24 Hours of usage of hall in a typical week

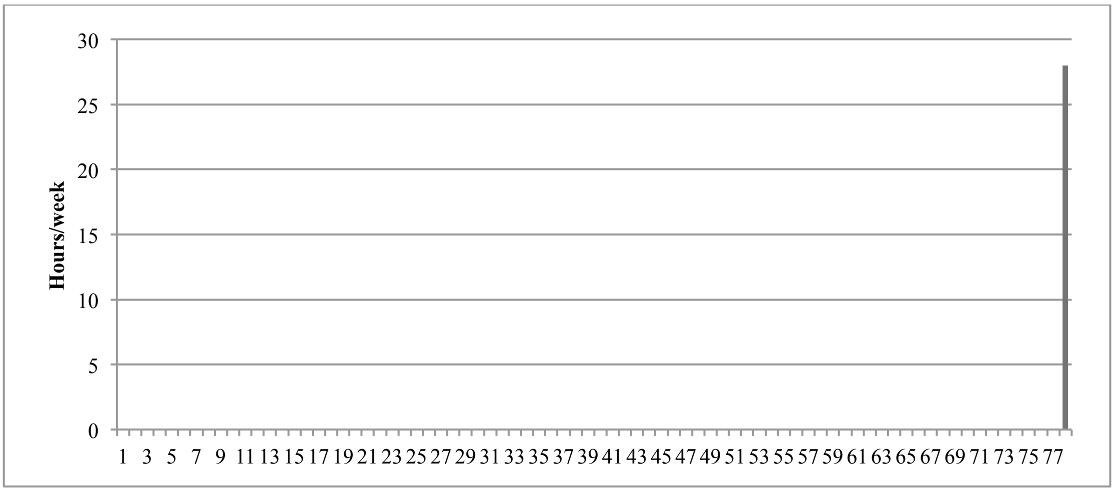


Figure C.25 Hours of usage of other unspecified space in a typical week

C.3 Space Heating

The heating hours of individual rooms in a typical week were recorded in the survey. Figure C.26 shows the min, max and average values of heating hours of each room. From the average values shown, the living room was heated for the longest time (46%), followed by kitchen (42%), bathroom/toilet (42%), dining room (41%), master bedroom (39%), bedroom (38%), hall (36%), guest room (35%), study/office (35%), utility room (13%), basement/storage areas (6%), conservatory (6%) and other unspecified room (4%).

The detailed space heating length is presented in an ascending order (Figure C.27 to Figure C.39), which sheds light on the ways rooms heated are distributed among all participants. Majority of these rooms were heated to various extents by most of the participants, such as master bedroom, living room, kitchen and bathroom/toilet. In contrast, a few rooms were only reported with heating hours by a few respondents, including basement/storage areas, conservatory, utility room, hall and other unspecified room.

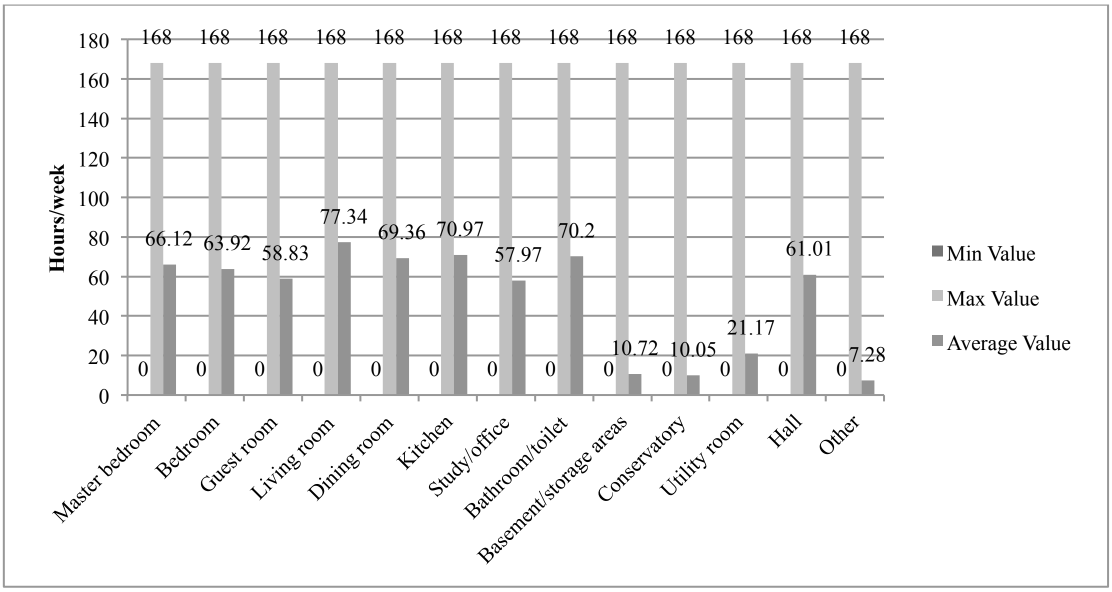


Figure C.26 Hours of heating of individual spaces at home in a typical week

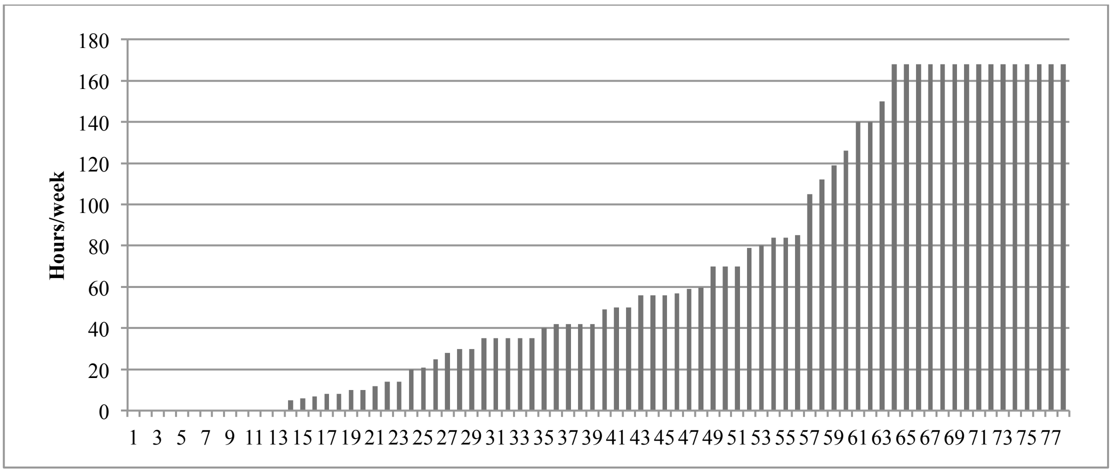


Figure C.27 Hours of heating of master bedroom in a typical week

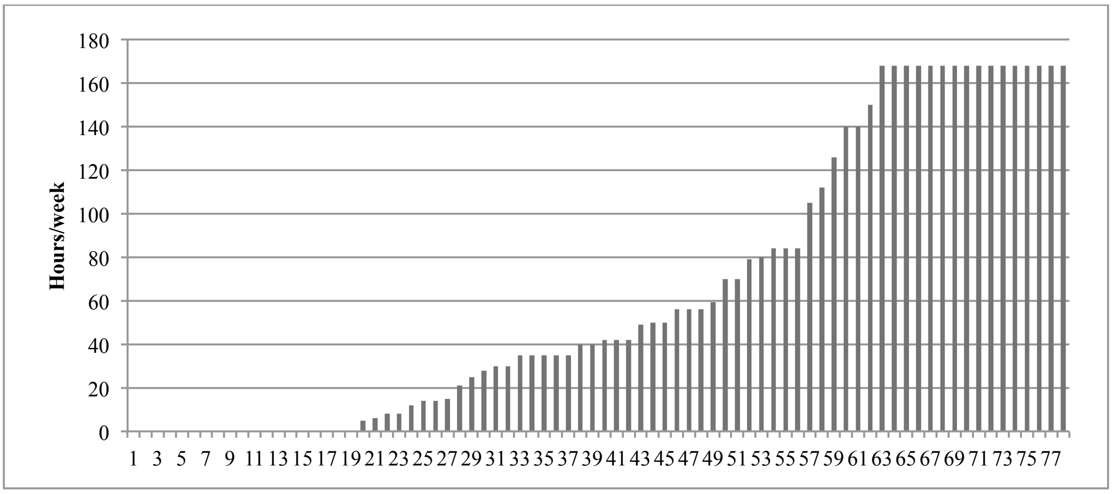


Figure C.28 Hours of heating of bedroom in a typical week

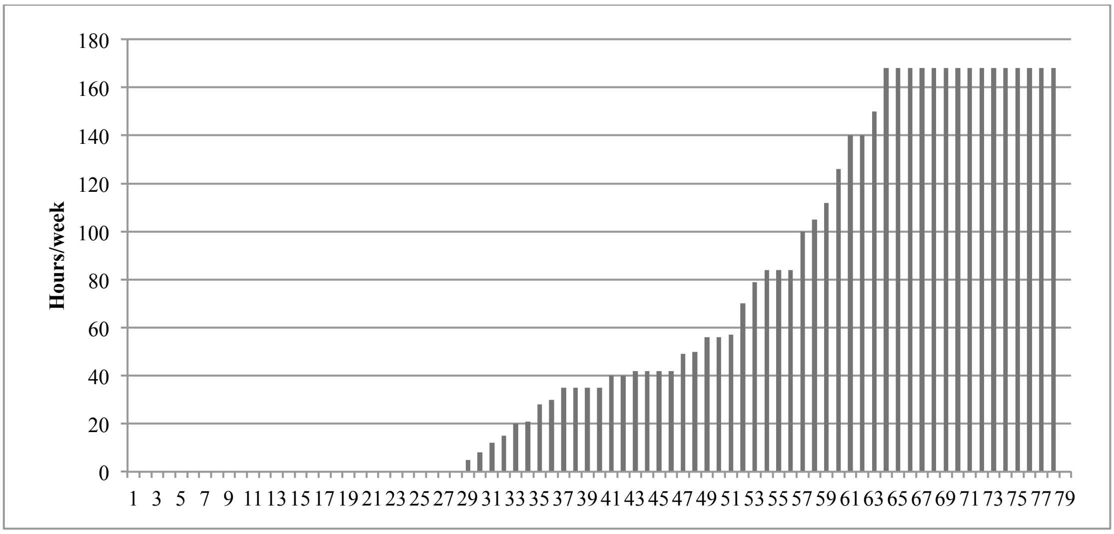


Figure C.29 Hours of heating of guest room in a typical week

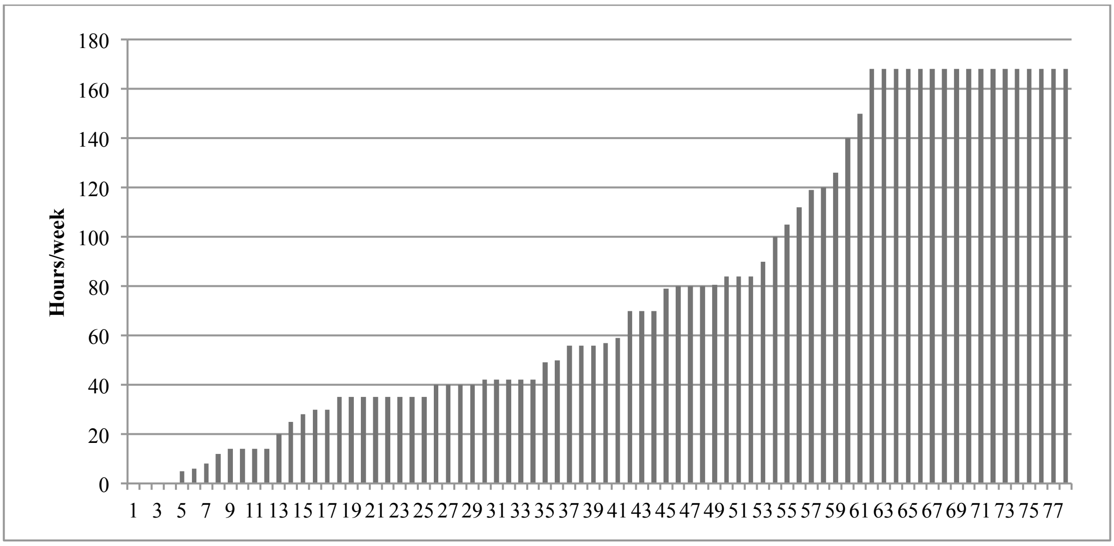


Figure C.30 Hours of heating of living room in a typical week

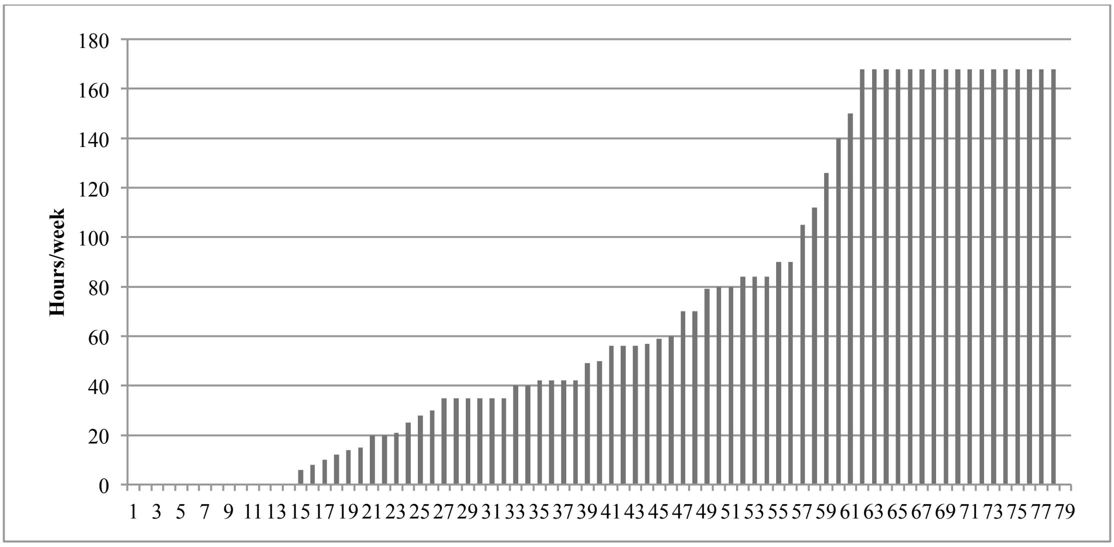


Figure C.31 Hours of heating of dining room in a typical week

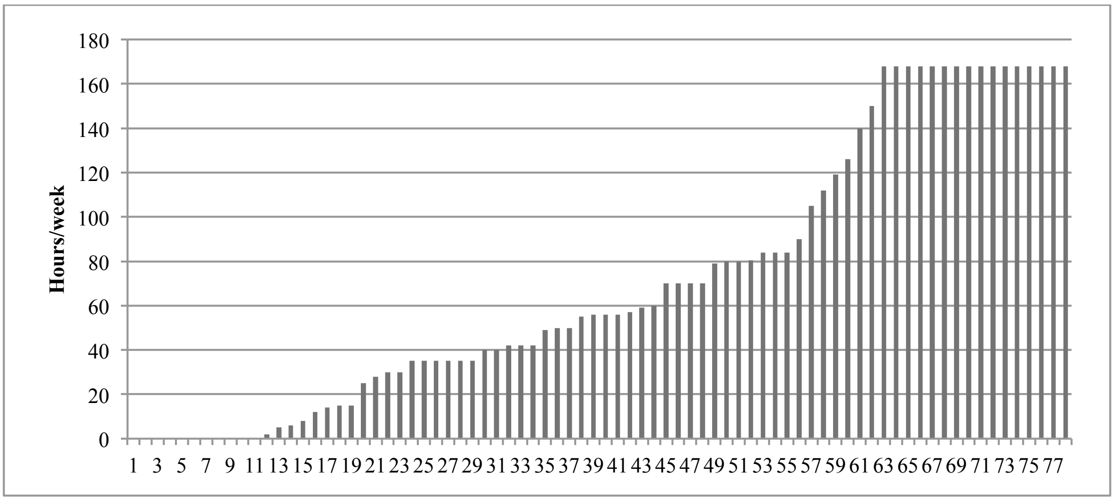


Figure C.32 Hours of heating of kitchen in a typical week

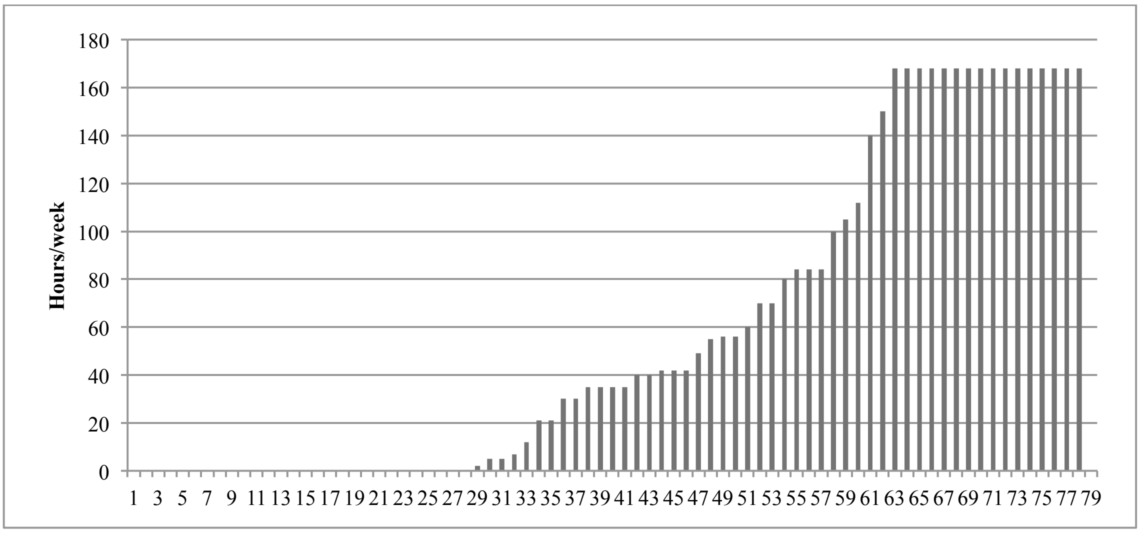


Figure C.33 Hours of heating of study/office in a typical week

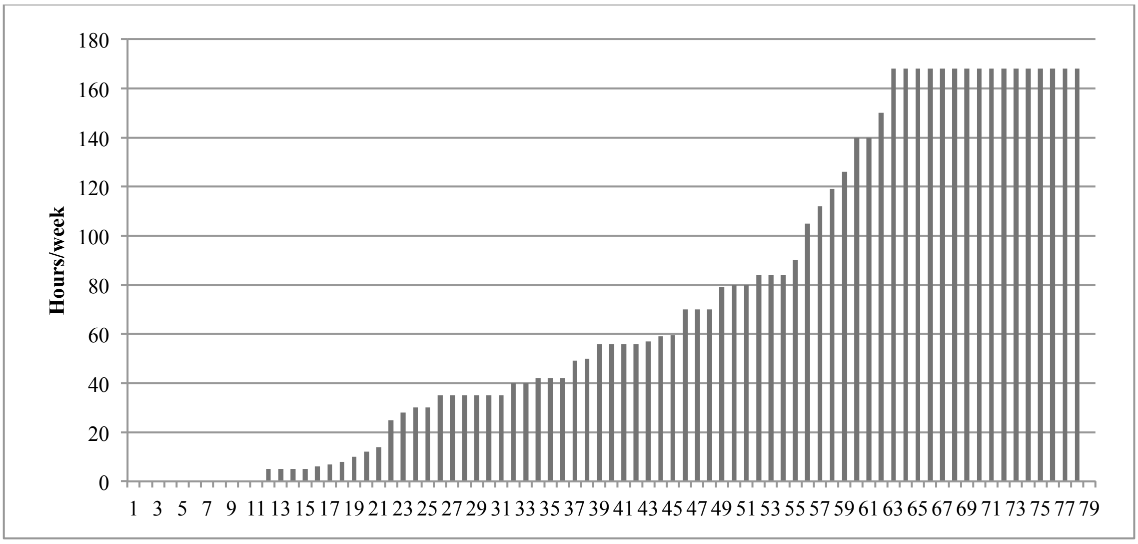


Figure C.34 Hours of heating of bathroom/toilet in a typical week

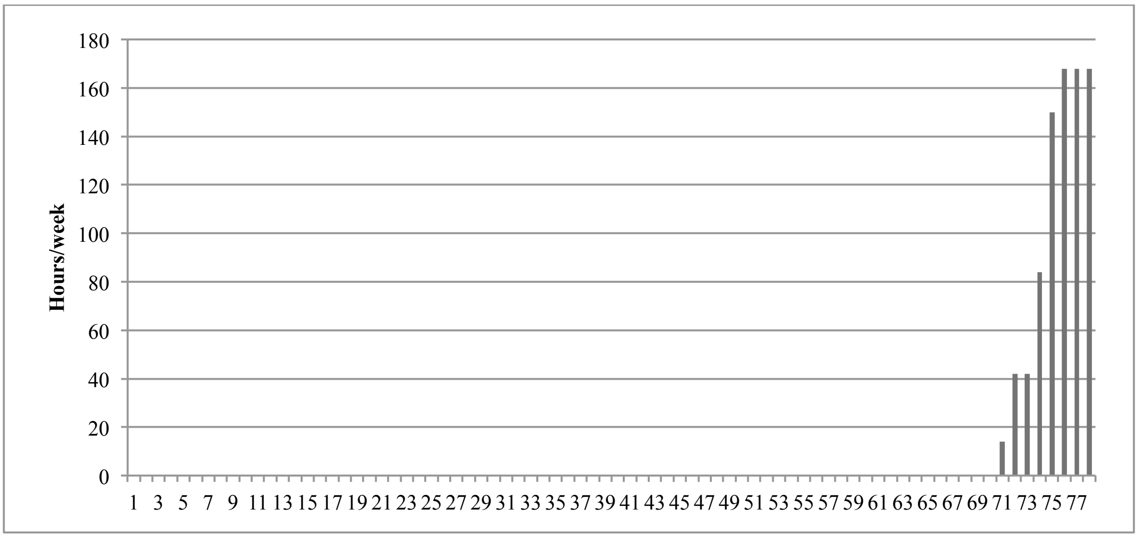


Figure C.35 Hours of heating of basement/storage areas in a typical week

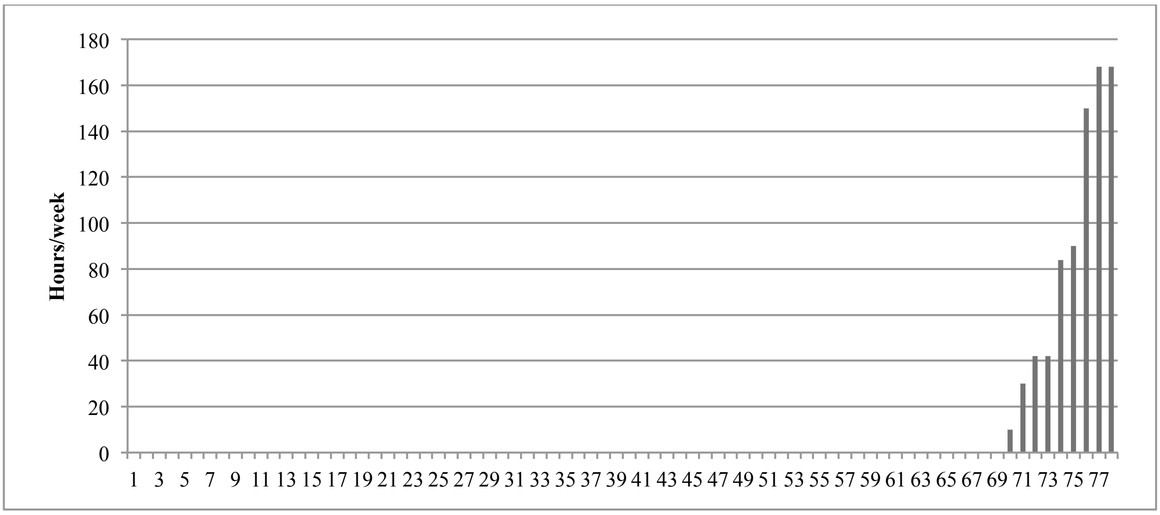


Figure C.36 Hours of heating of conservatory in a typical week

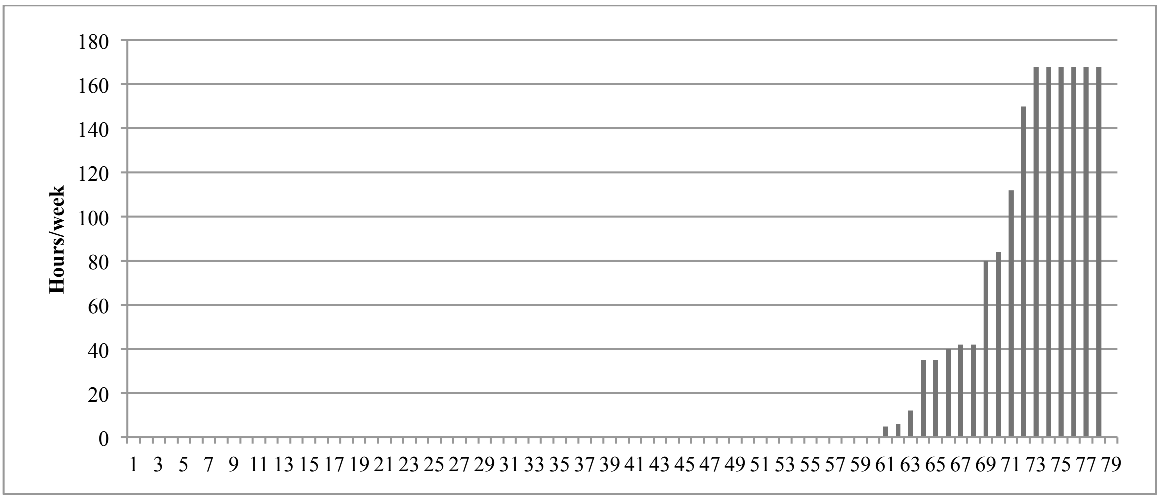


Figure C.37 Hours of heating of utility room in a typical week

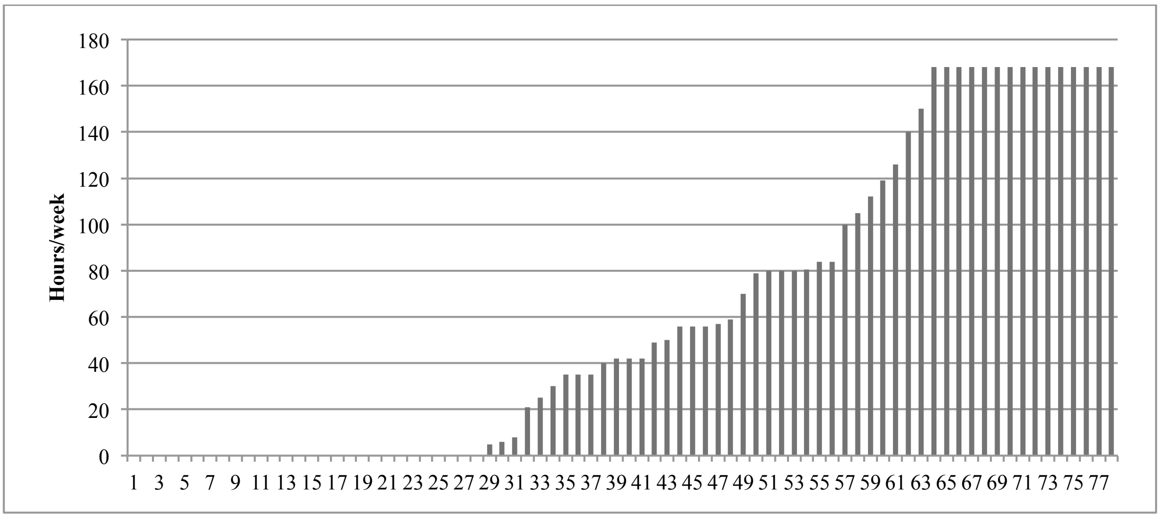


Figure C.38 Hours of heating of hall in a typical week

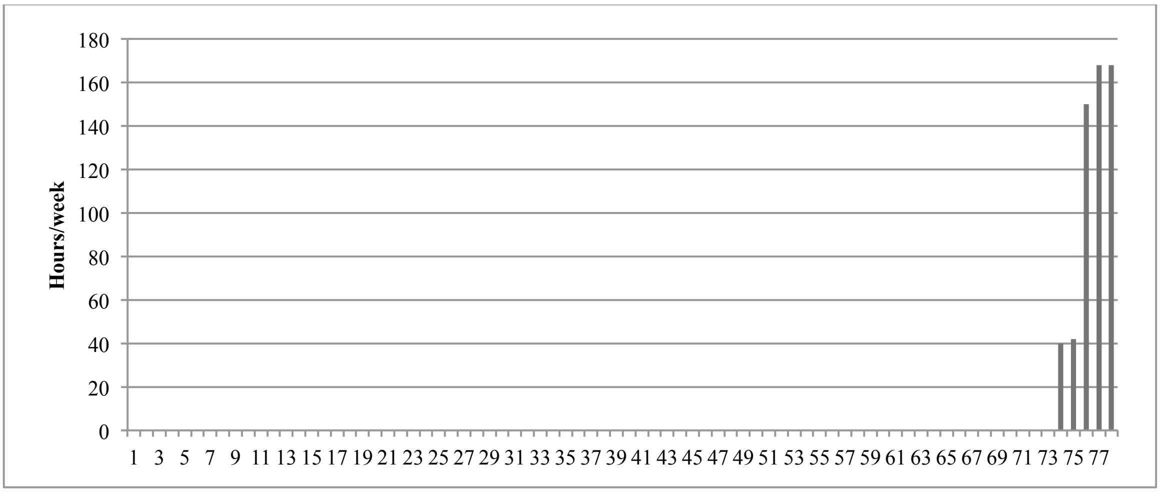


Figure C.39 Hours of heating of other unspecified room in a typical week

C.4 Clothing Level

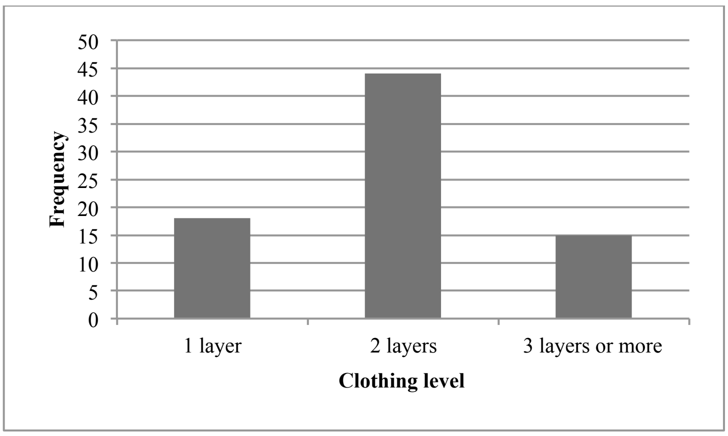


Figure C.40 Clothing levels

C.5 Level of Overall Satisfaction of Comfort, Thermal Comfort and Dwelling

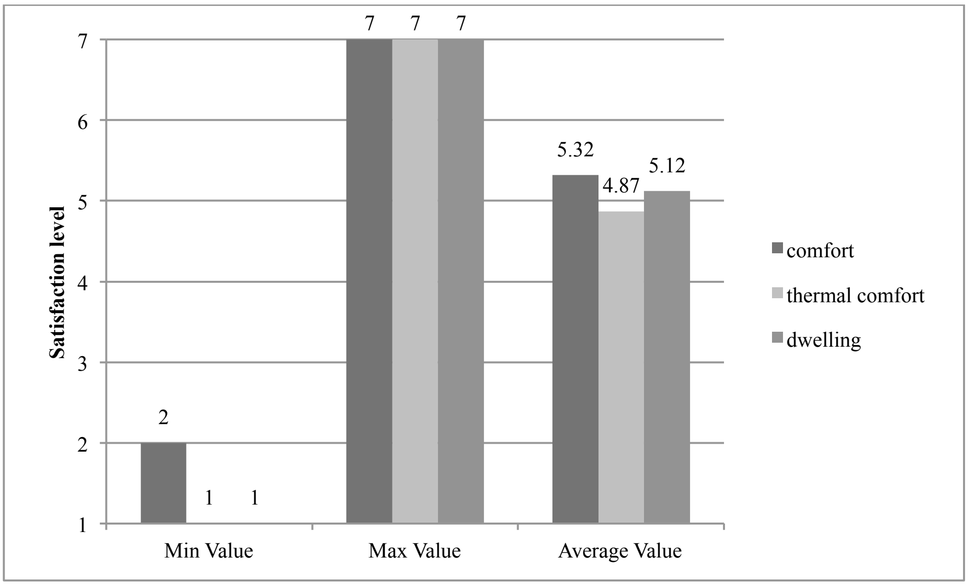


Figure C.41 Overall satisfaction levels of comfort, thermal comfort, and dwelling

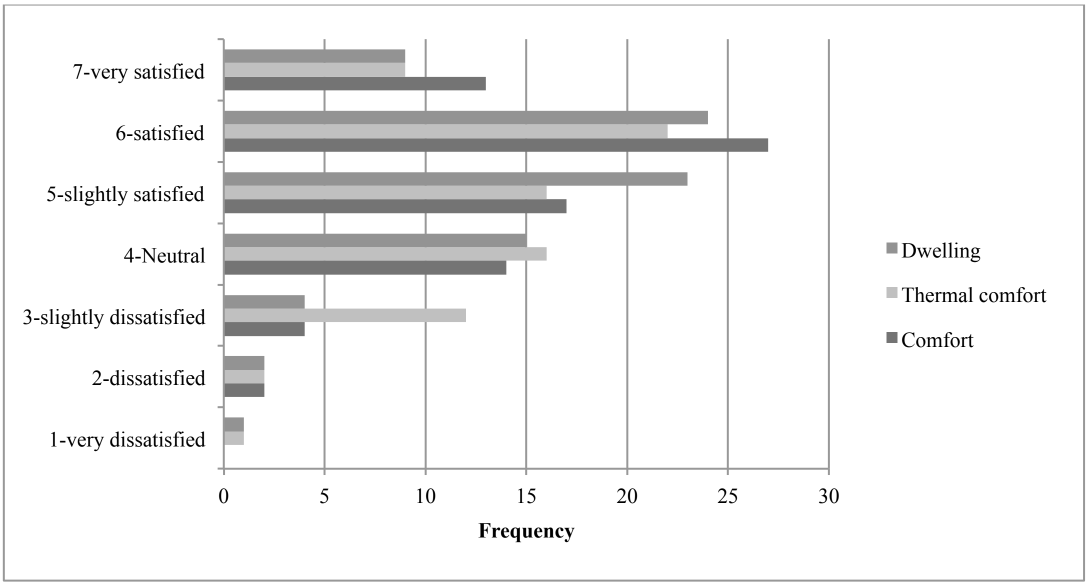


Figure C.42 Frequency of satisfaction levels of comfort, thermal comfort and dwelling

C.6 Level of Thermal Comfort and Temperature Sensation

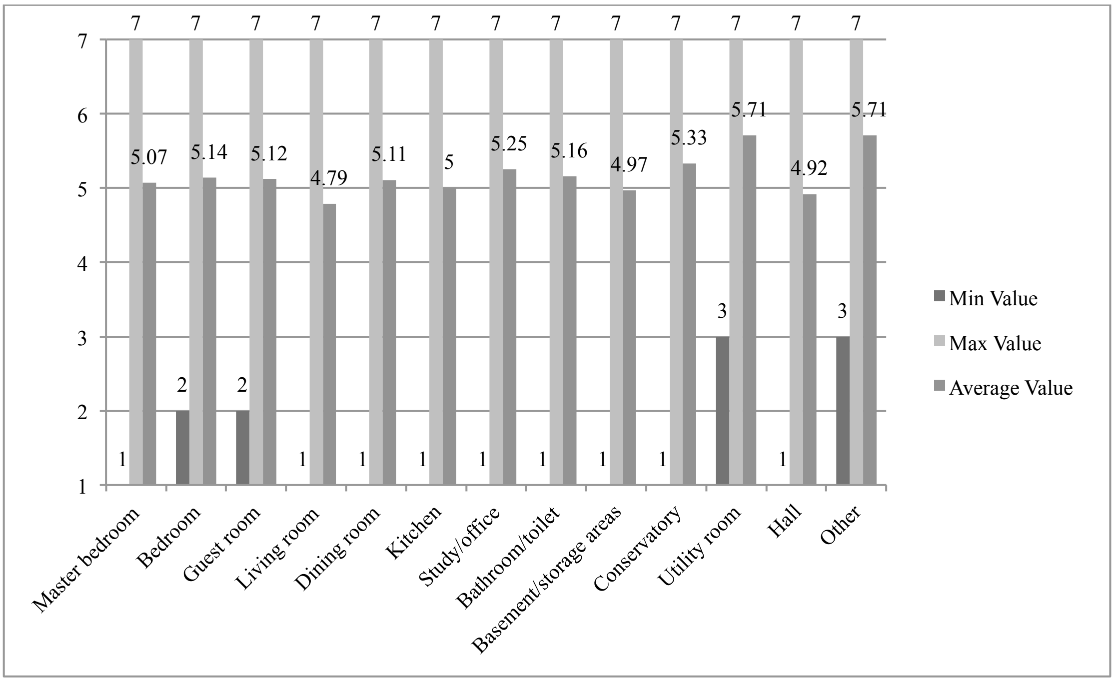


Figure C.43 Satisfaction levels of thermal comfort in individual rooms at home

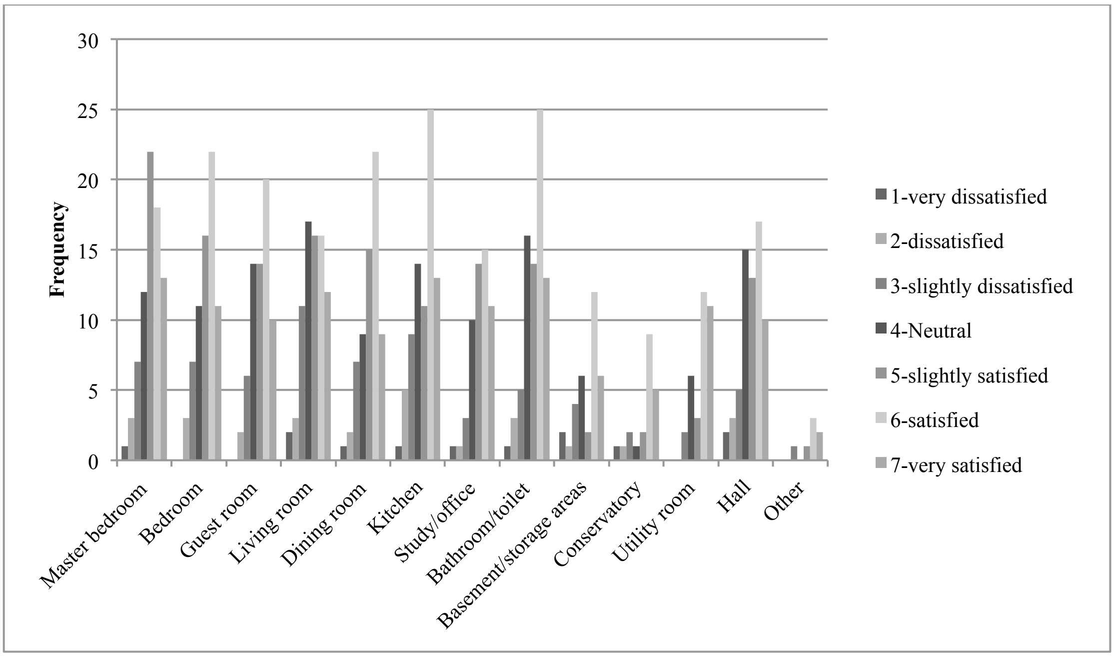


Figure C.44 Frequency of satisfaction levels of thermal comfort in individual rooms

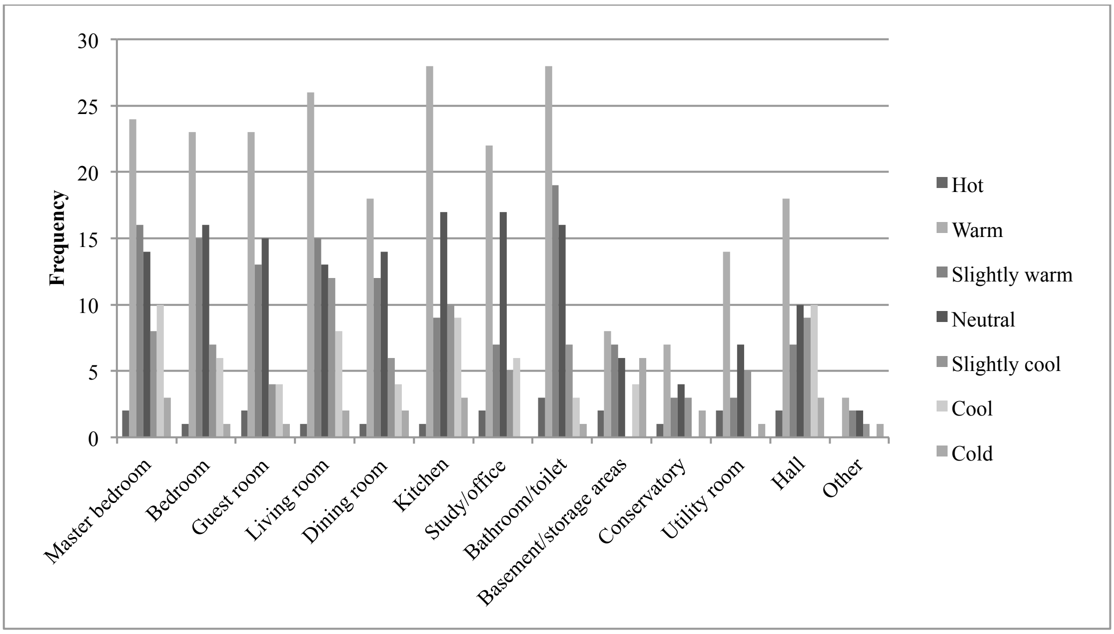


Figure C.45 Frequency of temperature sensations in individual rooms

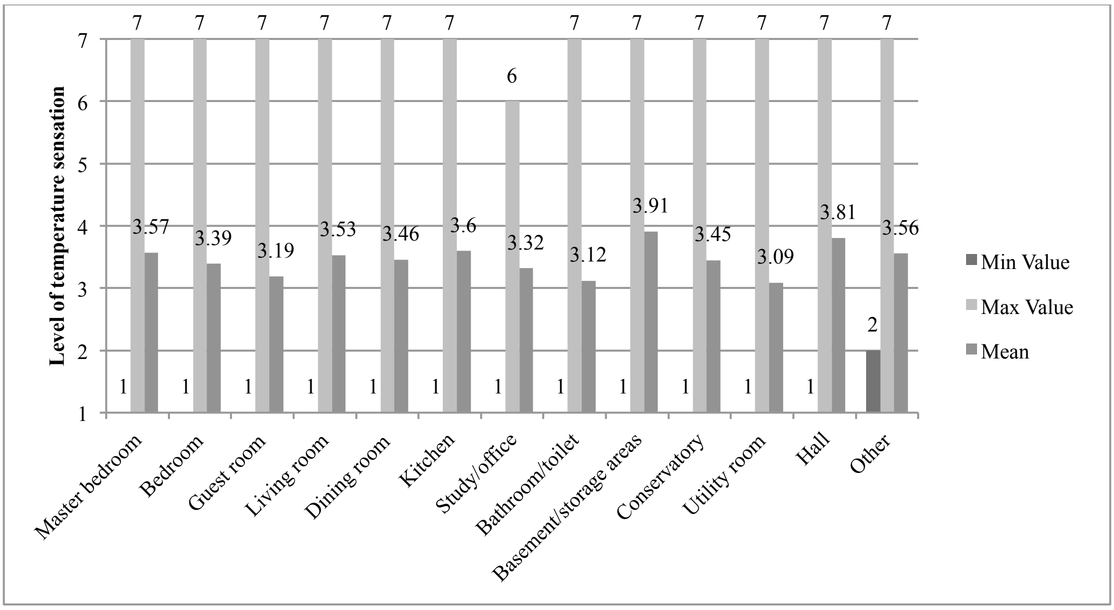


Figure C.46 Levels of temperature sensation in individual rooms

C.7 Relationship among Behaviours, Comfort and Dwellings

Table C.1 Household behaviour, correlation comfort and energy consumption

Behavioural Variable (hrs/wk)	Correlation Comfort Satisfaction (+)	Correlation Thermal Comfort Satisfaction (+)	Correlation Dwelling Satisfaction (+)	Correlation Energy Bill (+)
Working	ρ =.239* (-) N = 77		ρ =.245* (-) N = 78	
Cooking			ρ =.223* (-) N = 78	
Dining	ρ =.336** N = 77	ρ =.280* N = 78		
Sleep				
Personal hygiene				
Housework				
Exercise				
Social	ρ =.274* N = 77	ρ =.323** N = 78		
Master-bedroom usage				
Bedroom usage				ρ =.418** N = 48
Guest-room usage				
Living-room usage				
Dining-room usage	ρ =.254* N = 77			
Kitchen usage				ρ =.373** N = 48
Study/office usage				
Bathroom/toilet usage	ρ =.240* N = 77	ρ =.302** N = 78		
Basement/storage areas usage	ρ =.313** N = 77			ρ =.287* N = 48
Conservatory usage				
Utility-room usage	ρ =.285* N = 77			ρ =.312* N = 48
Hall usage			ρ =.240* N = 78	ρ =.334* N = 48
Master-bedroom heating				ρ =.495** N = 48
Bedroom heating				ρ =.585** N = 48
Guest-room heating	ρ =.268* N = 77	ρ =.313** N = 78		ρ =.462** N = 48
Living-room heating	ρ =.229* N = 77	ρ =.266* N = 78		ρ =.360* N = 48
Dining-room heating	ρ =.295** N = 77	ρ =.342** N = 78		ρ =.473** N = 48
Kitchen heating	ρ =.251* N = 77	ρ =.300** N = 78		ρ =.449** N = 48
Study/office heating		ρ =.273* N = 78		ρ =.516** N = 48
Bathroom/toilet heating				ρ =.380** N = 48
Basement/storage	ρ =.242*	ρ =.311**		

areas heating	N = 77	N = 78		
Conservatory heating				
Utility-room heating	ρ =.358** N = 77	ρ =.312** N = 78	ρ =.245* N = 78	ρ =.349* N = 48
Hall heating				ρ =.456** N = 48
Clothing level		ρ =.256* (-) N=77		
Total stay at home				

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table C.2 Correlation among comfort, thermal comfort, dwelling satisfaction and energy consumption

	Correlation Comfort Satisfaction (+)	Correlation Thermal Comfort Satisfaction (+)	Correlation Dwelling Satisfaction (+)	Correlation Energy Bill (+)
Correlation Comfort Satisfaction (+)		ρ=.830** N = 77	ρ=.555** N = 77	ρ=.289* N = 47
Correlation Thermal Comfort Satisfaction (+)	ρ=.830** N = 77		ρ=.397** N = 78	
Correlation Dwelling Satisfaction (+)	ρ=.555** N = 77	ρ=.397** N = 78		ρ=.298* N = 48
Correlation Energy Bill (+)	ρ=.289* N = 47		ρ=.298* N = 48	

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).
Note: energy efficiency rating unrelated to the tested characteristics

Table C.3 Heating behaviour, correlation occupant satisfaction and activities

Heating Behaviour in each room (hrs/week)	Correlation Thermal comfort satisfaction in each room (+)	Correlation Temperature Sensation in each room (-)	Correlation Space usage in each room (hrs/week) (+)	Correlation Master-bedroom Heating (hrs/week) (+)
Master-bedroom	ρ =.278* N = 76	ρ =.407** N = 77		ρ = 1 N = 78
Bedroom			ρ =.388** N = 78	ρ =.738** N = 78
Guest-room			ρ =.315** N = 78	ρ =.584** N = 78
Living-room	ρ =.239* N = 77	ρ =.265* N = 77	ρ =.294** N = 78	ρ =.697** N = 78
Dining-room			ρ =.352** N = 78	ρ =.607** N = 78
Kitchen	ρ =.243* N = 78	ρ =.287* N = 77	ρ =.258* N = 78	ρ =.685** N = 78
Study/office	ρ =.273* N = 55		ρ =.528** N = 78	ρ =.550** N = 78
Bathroom/toilet				ρ =.766** N = 78
Basement/storage areas		ρ =.356* N = 33	ρ =.305** N = 78	ρ =.263* N = 78

Conservatory			ρ =.632** N = 78	
Utility-room			ρ =.523** N = 78	ρ =.336** N = 78
Hall	ρ =.255* N = 65		ρ =.342** N = 78	ρ =.745** N = 78
Other			ρ =.411** N = 78	

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table C.4 Correlation thermal comfort, temperature sensation and space usage in each room

Correlation Thermal comfort in each room	Temperature Sensation satisfaction in each room (-)	Correlation Space usage in each room (hrs/week) (+)
Master-bedroom	ρ =.603** N = 76	
Bedroom	ρ =.529** N = 67	
Guest-room	ρ =.374** N = 60	
Living-room	ρ =.631** N = 76	
Dining-room	ρ =.574** N = 56	ρ =.263* N = 65
Kitchen	ρ =.710** N = 77	
Study/office	ρ =.624** N = 52	
Bathroom/toilet	ρ =.532** N = 76	ρ =.323** N = 77
Basement/storage areas	ρ =.512** N = 29	
Conservatory	ρ =.617** N = 17	
Utility-room	ρ =.595** N = 30	
Hall	ρ =.650** N = 59	

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table C.5 Correlation among comfort, energy consumption, household and dwelling characteristics

	Correlation Comfort Satisfaction (+)	Correlation Thermal Comfort Satisfaction (+)	Correlation Energy Bill (+)	Energy Efficiency Rating (+)	Correlation Dwelling Satisfaction (+)
Dwelling age					
Tenure type	ρ=292* (-) N = 76	ρ=.311*(-) N = 77			
Household type			ρ=.633** 48		

Household size	ρ=290* N = 76	ρ=.259* N = 77	ρ=.588** 48		
Participant age					
Household income			ρ=.426** 47		
Energy efficiency rating					
Dwelling type					
Dwelling orientation					
Total floor area	ρ=286* N = 77	ρ=.316** N = 78	ρ=.423** 48		
Energy bill	ρ=289* N = 47		1		

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).
Note: Tenure type (Owner occupied, private rented, rented from local authorities, rented from housing association); Household type (single, couple, family with children, single with children, extended family, non-family household); Dwelling type (end-terrace house, mid-terrace house, semi-detached house, detached house, maisonette, flat); Dwelling Orientation (south, north, east, west, south-east, south-west, north-east, north-west)

Table C.6 Household practices, correlation household characteristics

Behavioural Variable (hrs/wk)	Correlation Participant Age (+)	Correlation Participant Education (+)	Correlation Tenure Type (+)	Correlation Household Type (+)	Correlation Household size (+)	Correlation Household income (+)
Working						
Cooking	ρ=.273* N = 78					
Dining						
Sleep	ρ=.267*(-) N = 78					
Personal hygiene						
Housework						
Exercise						
Social			ρ=.255*(-) N = 77			
Master-bedroom usage						
Bedroom usage	ρ=.248*(-) N = 78			ρ =.561** N = 78	ρ =.595** N = 77	
Guest-room usage			ρ=.312**(-) N = 77	ρ=.369** N = 78	ρ =.485** N = 77	ρ =.309** N = 73
Living-room usage						
Dining-room usage	ρ=.271*(-) N = 78			ρ=.311** N = 78	ρ =.428** N = 77	ρ =.245* N = 73
Kitchen usage			ρ=.345**(-) N = 77	ρ =.325** N = 78	ρ =.338** N = 77	ρ =.231* N = 73
Study/office usage			ρ =.257*(-) N = 77			
Bathroom/toilet usage				ρ=.322** N = 78	ρ =.377** N = 77	
Basement/storage areas usage		ρ=.224*(-) N = 78			ρ =.270* N = 77	

Conservatory usage						
Utility-room usage		ρ =.275*(-) N = 78	ρ =.243*(-) N = 77		ρ =.278* N = 77	
Hall usage			ρ=.430**(-) N = 77	ρ =.308** N = 78	ρ =.346** N = 77	
Master-bedroom heating	ρ =.279*(-) N = 78			ρ =.393** N = 78	ρ =.366** N = 77	
Bedroom heating	ρ =.243*(-) N = 78			ρ =.518** N = 78	ρ =.425** N = 77	ρ =.290* N = 73
Guest-room heating	ρ=.327**(-) N = 78			ρ =.316** N = 78	ρ =.325** N = 77	ρ =.285* N = 73
Living-room heating			ρ =.241*(-) N = 77	ρ =.295** N = 78		ρ =.274* N = 73
Dining-room heating			ρ =.239*(-) N = 77	ρ =.309** N = 78	ρ =.270* N = 77	ρ =.395** N = 73
Kitchen heating			ρ =.237*(-) N = 77	ρ =.349** N = 78	ρ =.402** N = 77	ρ =.336** N = 73
Study/office heating				ρ =.386** N = 78	ρ =.303** N = 77	ρ =.299* N = 73
Bathroom/toilet heating				ρ =.347** N = 78	ρ =.264* N = 77	
Basement/storage areas heating					ρ =.407** N = 77	
Conservatory heating					ρ =.332** N = 77	
Utility-room heating					ρ =.367** N = 77	
Hall heating			ρ=.296**(-) N = 77	ρ =.288* N = 78	ρ =.271* N = 77	ρ =.306** N = 73

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Table C.7 Household practices, correlation dwelling characteristics

Behavioural Variable (hrs/wk)	Correlation Dwelling type (+)	Correlation Dwelling orientation (+)	Correlation Dwelling Age (+)	Correlation Energy Efficiency Rating (+)	Correlation Environmental Impact (CO2) Rating	Correlation Estimated Lighting Cost
Working						
Cooking	ρ=.224* N = 78					
Dining						ρ=.274* N = 78
Sleep						
Personal hygiene						ρ=.243* N = 78
Housework	ρ=.323** N = 78					
Exercise	ρ=.368** N = 78					
Social						
Master-bedroom usage				ρ=.278*(-) N = 78		
Bedroom usage						ρ=.331** N = 78

Guest-room usage						ρ =.315** N = 78
Living-room usage				ρ=.318**(-) N = 78	ρ =.242* (-) N = 77	
Dining-room usage						ρ =.408** N = 78
Kitchen usage	ρ=.249* N = 78					ρ =.296** N = 78
Study/office usage						ρ =.329** N = 78
Bathroom/toilet usage						ρ =.423** N = 78
Basement/storag e areas usage						ρ =.344** N = 78
Conservatory usage		ρ=.279*(-) N = 78				
Utility-room usage	ρ=.318** N = 78			ρ =.264* N = 78		ρ =.372** N = 78
Hall usage						ρ =.373** N = 78
Master-bedroom heating						ρ =.297** N = 78
Bedroom heating			ρ =.233* N = 78			ρ =.325** N = 78
Guest-room heating		ρ =.244* N = 78	ρ =.282* N = 78			ρ =.305** N = 78
Living-room heating			ρ =.344** N = 78			ρ =.440** N = 78
Dining-room heating		ρ =.232* N = 78	ρ =.358** N = 78			ρ =.470** N = 78
Kitchen heating			ρ =.303** N = 78			ρ =.343** N = 78
Study/office heating						ρ =.335** N = 78
Bathroom/toilet heating						ρ =.335** N = 78
Basement/storag e areas heating						ρ =.332** N = 78
Conservatory heating						
Utility-room heating						ρ =.383** N = 78
Hall heating						ρ =.324** N = 78
Clothing level	ρ =.238* N=77					

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

C.8 Survey Report

1. My overall satisfaction with the dwelling and its physical condition

#	Answer	Min Value	Max Value	Average Value	Standard Deviation	Responses
1		1.00	7.00	5.12	1.27	78

2. My overall satisfaction with my thermal comfort at home

#	Answer	Min Value	Max Value	Average Value	Standard Deviation	Responses
1		1.00	7.00	4.87	1.42	78

3. How satisfied are you with your thermal comfort in each place at home? (choose rooms that are applicable)

#	Answer	Min Value	Max Value	Average Value	Standard Deviation	Responses
1	Master Bedroom	1.00	7.00	5.07	1.43	76
2	Bedroom	2.00	7.00	5.14	1.38	70
3	Guest Room	2.00	7.00	5.12	1.33	66
4	Living room	1.00	7.00	4.79	1.54	77
5	Dining room	1.00	7.00	5.11	1.42	65
6	Kitchen	1.00	7.00	5.00	1.56	78
7	Study/Office	1.00	7.00	5.25	1.38	55
8	Bathroom/Toilet	1.00	7.00	5.16	1.42	77
9	Basement/Storage areas	1.00	7.00	4.97	1.76	33
10	Conservatory	1.00	7.00	5.33	1.74	21
11	Utility Room	3.00	7.00	5.71	1.27	34
12	Hall	1.00	7.00	4.92	1.53	65
13	Other(please specify)	3.00	7.00	5.71	1.38	7

4. How do you find the temperature in each place at home? (choose rooms that are applicable)

#	Question	Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold	Total Responses	Mean
1	Master Bedroom	2	24	16	14	8	10	3	77	3.57
2	Bedroom	1	23	15	16	7	6	1	69	3.39
3	Guest Room	2	23	13	15	4	4	1	62	3.19
4	Living room	1	26	15	13	12	8	2	77	3.53
5	Dining room	1	18	12	14	6	4	2	57	3.46
6	Kitchen	1	28	9	17	10	9	3	77	3.60
7	Study/Office	2	22	7	17	5	6	0	59	3.32
8	Bathroom/Toilet	3	28	19	16	7	3	1	77	3.12
9	Basement/Storage areas	2	8	7	6	0	4	6	33	3.91
10	Conservatory	1	7	3	4	3	0	2	20	3.45
11	Utility Room	2	14	3	7	5	0	1	32	3.09
12	Hall	2	18	7	10	9	10	3	59	3.81
13	Other(please specify)	0	3	2	2	1	0	1	9	3.56

Statistic	Master Bedroom	Bedroom	Guest Room	Living room	Dining room	Kitchen	Study/ Office	Bathroom/Toilet	Basement/ Storage areas	Conservatory	Utility Room	Hall	Other(please specify)
Min Value	1	1	1	1	1	1	1	1	1	1	1	1	2
Max Value	7	7	7	7	7	7	6	7	7	7	7	7	7
Mean	3.57	3.39	3.19	3.53	3.46	3.60	3.32	3.12	3.91	3.45	3.09	3.81	3.56
Variance	2.51	1.92	1.83	2.28	2.07	2.51	1.98	1.66	3.96	2.89	2.09	2.95	2.78
Standard Deviation	1.58	1.38	1.35	1.51	1.44	1.58	1.41	1.29	1.99	1.70	1.44	1.72	1.67
Total Responses	77	69	62	77	57	77	59	77	33	20	32	59	9

5. What is your clothing level at home?

#	Answer		Response	%
1	1 layer		18	23%
2	2 layers		44	57%
3	3 layers or more		15	19%
	Total		77	100%

Statistic	Value
Min Value	1
Max Value	3
Mean	1.96
Variance	0.43
Standard Deviation	0.66
Total Responses	77

6. My overall satisfaction with my comfort at home

#	Answer	Min Value	Max Value	Average Value	Standard Deviation	Responses
1		2.00	7.00	5.32	1.25	77

7. Do you have any comments on your comfort at home?
Text Response
I should, perhaps, turn the heating up
Insulation poor - single glazing
warm to necessary, not easy to maintain heat
I live in an old house with original sash windows
Central heating new - a little hard to adjust
Satisfactory
Recently renovated house, very comfortable
1-glazed very old simple windows, elctric heating
It's better when the heating is on! can be colder with big window& radiators placed near them
I believe in keeping fossil fuel use on the planet to a minimum so I wear a jumper instead of turning on the heating!!
Those areas where I'm not comfortable are because I haven't finished renovating the windows and doors yet.
The spaces we have created are very comfortable. However, comfort is not solely defined by a space being the correct temperature! Lighting and ambience play as much a part.
I get the impression you are thinking of winter. Of course I wear fewer layers on hot days (and vice versa). In fact on really hot days it can be difficult to keep our house cool enough just by opening windows (we don't have air conditioning, like most UK homes)
no
our house gets cold, but I love my house
Honeywell thermostat set to 21*C
not satisfied because of high bills! lots of leakage
Heating temperature all controlled by living room thermostat, 19*C day 13*C night
no
House has nice fuel and functions, cold southerns
Very cold ground floor
Large glass windows, south facing, gets hot.
badly insulated
Very bad insulation, especially in the living room
no
Too cold downstairs without heating on: the heating is on 1st floor (originally built); hot air rises; trees in backyard block sun.
Bad insulation
Small therefore easy to clear
No
old home, bad air quality
insulation + double glazed windows would be good
Triple glazing would be better than double; better fitting doors/ windows would help!
We live here because it is so comfortable
Draft insulation is not good; chimney designed poorly; cold is still coming in; sliding doors have draughty issues; no place to dry clothes; energy efficiency is not good; sound insulation is very good
One part of the house is not heated as the pump is not sufficiently powerful to provide even distribution of heat in the house
Visual comfort
Heat loss via single brick walls & suspended floors is negative, and causes more draughts than is desirable
drafty

Statistic	Value
Total Responses	38

8. How many hours of a typical week do you spend at home?
Text Response
85
98
140
the majority - 20 hours/day
110
I am at home most days: I work from home
108
81
135
110
105
70
84 (inc. sleeping) (hard to answer)
74
115
140
18/24
60
140
138
100
105
100
145 (Most - work from home)
73
All the nights + 3.5 hours a day
130
110
100
140 (About 20 hours a day - I works at home)
most of the time
140
126
84
70
67.5
140
140
120
105
150
84
work from home 24 hours/day
91
140
160
115.5
100
70
100
120
120
100
129
131
95
119
140
84
133
100
129 (most - I work from home)
105
126
125

120
138 (husband); wife's more.
180
120
100
112
All week - work at home
140
90
140
90% -- retired
126

Statistic	Value
Total Responses	77

9. In a typical week, how many hours of your total time at home has been spent on the following activities:

#	Answer	Min Value	Max Value	Average Value	Standard Deviation
1	Working (computer based or paper based)	0.00	60.00	18.18	17.17
2	Cooking	0.00	21.00	8.74	5.15
3	Dining	0.00	60.00	8.82	7.19
4	Sleep	5.00	84.00	51.08	10.87
5	Personal Hygiene	0.00	20.00	5.62	3.16
6	Housework	0.00	56.00	6.29	7.34
7	Exercise	0.00	45.00	3.32	6.96
8	Social	0.00	35.00	5.97	6.34
9	Other (e.g.hobbies, leisure activities) - please specify	0.00	45.50	7.36	9.29

10. Over the last few months, how many hours of a typical week have the following places been used? (choose rooms that are applicable)

#	Answer	Min Value	Max Value	Average Value	Standard Deviation
1	Master Bedroom	0.00	168.00	54.67	22.72
2	Bedroom	0.00	168.00	40.92	34.74
3	Guest Room	0.00	168.00	19.79	31.65
4	Living room	0.00	100.00	33.78	24.21
5	Dining room	0.00	84.00	14.87	18.63
6	Kitchen	0.00	100.00	25.16	20.90
7	Study/Office	0.00	84.00	14.08	18.98
8	Bathroom/Toilet	0.00	63.00	11.96	10.87
9	Basement/Storage areas	0.00	168.00	3.02	19.74
10	Conservatory	0.00	49.00	1.35	6.56
11	Utility Room	0.00	56.00	1.70	6.98
12	Hall	0.00	70.00	3.20	10.79
13	Other(please specify)	0.00	28.00	0.36	3.17

11. Over the last few months, how many hours of a typical week have the following places been heated? (choose rooms that are applicable)					
#	Answer	Min Value	Max Value	Average Value	Standard Deviation
1	Master Bedroom	0.00	168.00	66.12	61.71
2	Bedroom	0.00	168.00	63.92	64.19
3	Guest Room	0.00	168.00	58.83	65.40
4	Living room	0.00	168.00	77.34	58.11
5	Dining room	0.00	168.00	69.36	62.30
6	Kitchen	0.00	168.00	70.97	60.19
7	Study/Office	0.00	168.00	57.97	65.87
8	Bathroom/Toilet	0.00	168.00	70.20	61.68
9	Basement/Storage areas	0.00	168.00	10.72	37.62
10	Conservatory	0.00	168.00	10.05	34.33
11	Utility Room	0.00	168.00	21.17	49.76
12	Hall	0.00	168.00	61.01	64.81
13	Other(please specify)	0.00	168.00	7.28	31.86

12. Have any energy efficient measures been installed to improve your home's performance?
Text Response
loft insulation, cavity wall insulation
No
insulation
secondary glazing
Loft insulated, we have tried to import/maintain sash windows
No
yes, extra cladding in loft
Yes, roof insulation/ solar water heating/ PV roof panels/ secondary double glazing
No
insulation
not that i'm aware of!
no
Yes, thermostats, underfloor heating in kitchen, underfloor insulation throughout ground floor, inprovements to sash windows, insulation in attic
Yes. Insulation. Windows draft proofed. New boiler.
Insulation in loft, radiators have thermostats and are timed e.g. to reduce temperature at night
no
Insulation in loft, double glazing, upgrading boiler, lighting (energy efficient lightbulbs)
yes
loft insulation and draught proofing around front door and sash windows
No, depends on landlord
Thermostat + some double glazing
None
None (probably double glazed windows)
no
Roof insulation, double glazing, upgraded boiler, pipe insulation
Loft insulation
Not that I'm aware of. rented house
Double glazing throughout; High grade roof insulation; Honeywell thermostat
Double paned windows, insulation
Loft insulation, some new windows
None
N/A
No
Condensing boiler, floor insulation, wall insulation, double glazing
No
I dont know
Double glazing, roof lagged
NO
Double glazing, roof insulation, draft pricking
Thick insulations
Roof insulation, some double glazing
Double glazing
No
Improved loft insulation
I dont know
No
No
None
A decent boiler some years ago
New boiler
No
Low voltage LED lighting
N/A
No
Insulation, double-glazed windows
None
No
Not since purchase
No
double glazing; external wall insulation; condensing boilers; no extra added stuff since it's ben built
None
N/A
No
N/A

Thermostat, Condensing boiler, Roof insulation
Floor insulation, Double glazing
Insulation, Thermostat in each room, Underfloor heating, solar panel
yes - double glazing; loft insulation
no

Statistic	Value
Total Responses	69

13. Dwelling age

#	Answer		Response	%
1	pre-1919		44	56%
2	1919-44		6	8%
3	1945-64		2	3%
4	1965-80		6	8%
5	1981-90		2	3%
6	post 1990		18	23%
	Total		78	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	2.62
Variance	4.50
Standard Deviation	2.12
Total Responses	78

14. Tenure type

#	Answer		Response	%
1	Owner occupied		51	66%
2	Private rented		25	32%
3	Rented from local authorities		0	0%
6	Rented from housing association		1	1%
	Total		77	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	1.39
Variance	0.50
Standard Deviation	0.71
Total Responses	77

15. Household type

#	Answer		Response	%
1	single		8	10%
2	couple		20	26%
3	family with children		44	56%
4	single with children		1	1%
5	non-family household		4	5%
6	extended family		1	1%
	Total		78	100%

Statistic	Value
Min Value	1
Max Value	6
Mean	2.69
Variance	0.92
Standard Deviation	0.96
Total Responses	78

16. Household size

#	Answer		Response	%
1	1 person		7	9%
2	2 people		21	27%
3	3 people		8	10%
4	4 people		25	32%
5	5 people or above		16	21%
	Total		77	100%

Statistic	Value
Min Value	1
Max Value	5
Mean	3.29
Variance	1.73
Standard Deviation	1.32
Total Responses	77

17. What is your age? (U.S. Census 7 Categories)

#	Answer		Response	%
1	Under 15 years		3	4%
2	15 to 24 years		7	9%
3	25 to 34 years		11	14%
4	35 to 44 years		23	29%
5	45 to 54 years		16	21%
6	55 to 64 years		11	14%
7	65 years and over		7	9%
	Total		78	100%

Statistic	Value
Min Value	1
Max Value	7
Mean	4.32
Variance	2.35
Standard Deviation	1.53
Total Responses	78

18. What is the highest level of education you have completed?

#	Answer		Response	%
1	Less than High School		5	6%
2	High School / GED		4	5%
5	Bachelor Degree		24	31%
6	Masters Degree		24	31%
7	Doctoral Degree		14	18%
8	Professional Degree (JD, MD)		7	9%
	Total		78	100%

Statistic	Value
Min Value	1
Max Value	8
Mean	5.53
Variance	3.08
Standard Deviation	1.76
Total Responses	78

19. Working status

#	Answer		Response	%
1	Unemployed		13	17%
2	Part-time		16	21%
3	Full-time		31	40%
4	Retired		8	10%
5	Student		9	12%
	Total		77	100%

Statistic	Value
Min Value	1
Max Value	5
Mean	2.79
Variance	1.43
Standard Deviation	1.20
Total Responses	77

20. Where are you employed?

#	Answer		Response	%
1	PRIVATE-FOR-PROFIT company, business or individual, for wages, salary or commissions		15	29%
2	PRIVATE-NOT-FOR-PROFIT, tax-exempt, or charitable organization		10	20%
3	GOVERNMENT employee		11	22%
6	SELF-EMPLOYED in own NOT INCORPORATED business, professional practice, or farm		6	12%
7	SELF-EMPLOYED in own INCORPORATED business, professional practice, or farm		6	12%
8	Working WITHOUT PAY in family business or farm		3	6%
	Total		51	100%

Statistic	Value
Min Value	1
Max Value	8
Mean	3.33
Variance	5.79
Standard Deviation	2.41
Total Responses	51

21. Please indicate your occupation:

#	Answer		Response	%
1	Managers		10	18%
2	Professionals		33	60%
3	Technicians and associate professionals		6	11%
4	Clerical support workers		3	5%
5	Service and sales workers		3	5%
6	Skilled agricultural, forestry and fishery workers		0	0%
7	Craft and related trades workers		0	0%
8	Plant and machine operators, and assemblers		0	0%
9	Armed forces occupations		0	0%
10	Elementary occupations		0	0%
	Total		55	100%

Statistic	Value
Min Value	1
Max Value	5
Mean	2.20
Variance	0.98
Standard Deviation	0.99
Total Responses	55

22. What is your combined annual household income?

#	Answer		Response	%
1	Less than £15,000		10	14%
2	£15,000 – 19,999		2	3%
3	£20,000 – 24,999		3	4%
4	£25,000 – 29,999		4	5%
5	£30,000 – £49,999		16	22%
9	£50,000 or more		38	52%
	Total		73	100%

Statistic	Value
Min Value	1
Max Value	9
Mean	6.32
Variance	9.39
Standard Deviation	3.06
Total Responses	73

23. How much is your energy bill per year?
Text Response
Gas - estimated annual consumption (march 2014) 10,338; Electricity - estimated annual consumption (march 2014) 2,359; I pay by direct debit £51-65 monthly
£600
£1600 (electricity + gas)
£750
£1300 (gas + electricity)
Approx. £600 P.A. (£50 PCM) gas/elec.
£720
£700
£3,000 (our house is 4,000 square foot)
£900
£1300
£500 approx
unknown. gas&electricity is £90 direct debit however account is in credit
Gas bill = 660, gas powered heating throughout, some costs for log burner in sitting room in winter, elec bill = 600
£1,250
£2500
1500
£1,000
£1,500
high bills
£2,000
£1454.25 (Monthly: £181.83, 259.11, 211.96, 101.38, 70.94, 129.31, 99.57, 150.18, 249.97 gas+ electricity)
£1,800 (£1,200 electricity & gas, £600 water)
£1,100
£1,500
£900
£140
£2,748 (£229 per month)
£600 (£150- 3months)
£1,000 (I think)
I dont know
£3840 [£80/per person/ per month (inc. council tax)]
£624 (£52 per month)
£800
£4,000
I dont know
Not sure
£1,000
£1,200
£1,000
Inc. in the rent
£1,400
£2,000 (approx.) (too much!)
approx. £1,500
£2,000
£2,500
£500
£1,500
£1,000
£1,800
£2,000 (inc. electricity & gas)
£2,700
£1956

Statistic	Value
Total Responses	53

24. Energy Efficiency Rating

#	Question	A	B	C	D	E	F	G	Total Responses	Mean
1	Current	0	3	19	29	17	10	0	78	4.15
2	Potential	0	24	22	20	9	3	0	78	3.29

Statistic	Current	Potential
Min Value	2	2
Max Value	6	6
Mean	4.15	3.29
Variance	1.12	1.30
Standard Deviation	1.06	1.14
Total Responses	78	78

25. Environmental Impact (CO_2) Rating

#	Question	A	B	C	D	E	F	G	Total Responses	Mean
1	Current	0	2	18	20	23	14	0	77	4.38
2	Potential	0	16	23	20	14	4	0	77	3.57

Statistic	Current	Potential
Min Value	2	2
Max Value	6	6
Mean	4.38	3.57
Variance	1.24	1.35
Standard Deviation	1.11	1.16
Total Responses	77	77

26. Dwelling type

#	Answer		Response	%
1	End-terrace house		10	13%
2	Mid-terrace house		52	67%
3	Semi-detached house		6	8%
4	Detached house		6	8%
5	Maisonette		1	1%
9	Flat		3	4%
	Total		78	100%

Statistic	Value
Min Value	1
Max Value	9
Mean	2.41
Variance	2.37
Standard Deviation	1.54
Total Responses	78

27. Total floor area (m^2)
Text Response
74
117
168
112
175
171
91
172
70
90
89
152
86
82
224
76
112
118
270
73
96
192
107
130
135
118
98
119
81
97
62
60
45
110
111
60
89
202
109
88
202
110
110
46
231
144
171
93
94
93
58
86
78
104
82
204
143
219
125
128
212
125
235
186
186

235
235
127
125
125
179
186
186
93
189
197
140
129

Statistic	Value
Total Responses	78

28. Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home - per year (Current)

#	Answer	Min Value	Max Value	Average Value	Standard Deviation
1	Energy use (kWh/m2)	93.00	549.00	277.51	115.59
2	Carbon dioxide emissions (tonnes)	1.50	16.00	6.16	3.49
3	Lighting (£)	24.00	241.00	100.44	43.12
4	Heating (£)	220.00	2,698.00	900.55	551.90
5	Hot water (£)	68.00	346.00	139.19	58.19

29. Estimated energy use, carbon dioxide (CO_2) emissions and fuel costs of this home - per year (Potential)

#	Answer	Min Value	Max Value	Average Value	Standard Deviation
1	Energy use (kWh/m^2)	0.00	434.00	213.79	92.29
2	Carbon dioxide emissions (tonnes)	0.60	14.00	4.43	2.73
3	Lighting (£)	24.00	121.00	64.12	22.10
4	Heating (£)	188.00	2,370.00	705.05	387.89
5	Hot water (£)	56.00	244.00	105.33	30.00

30. Elements current performance - Energy efficiency

#	Question	Very poor	Poor	Average	Good	Very good	Total Responses	Mean
1	Walls - a	51	3	0	13	11	78	2.10
2	Walls - b	6	2	8	13	0	29	2.97
3	Roof - pitched	16	5	15	18	4	58	2.81
4	Roof - room(s)	16	5	5	33	0	59	2.93
6	Windows	19	17	20	21	1	78	2.59
7	Main heating	0	0	7	53	18	78	4.14
8	Main heating controls	2	12	36	24	4	78	3.21
9	Secondary heating	0	0	0	0	0	0	0.00
10	Hot water	2	5	11	41	19	78	3.90
11	Lighting	10	13	25	12	18	78	3.19

Statistic	Walls - a	Walls - b	Roof - pitched	Roof - room(s)	Windows	Main heating	Main heating controls	Secondary heating	Hot water	Lighting
Min Value	1	1	1	1	1	3	1	-	1	1
Max Value	5	4	5	4	5	5	5	-	5	5
Mean	2.10	2.97	2.81	2.93	2.59	4.14	3.21	0.00	3.90	3.19
Variance	2.61	1.39	1.77	1.75	1.36	0.30	0.74	0.00	0.87	1.74
Standard Deviation	1.62	1.18	1.33	1.32	1.17	0.55	0.86	0.00	0.93	1.32
Total Responses	78	29	58	59	78	78	78	0	78	78

31. Elements current performance - Environmental

#	Question	Very poor	Poor	Average	Good	Very good	Total Responses	Mean
1	Walls - a	36	2	0	9	11	58	2.26
2	Walls - b	4	2	7	8	0	21	2.90
3	Roof - pitched	15	3	11	11	1	41	2.51
4	Roof - room(s)	11	4	4	25	0	44	2.98
6	Windows	15	14	13	15	1	58	2.53
7	Main heating	0	0	1	39	18	58	4.29
8	Main heating controls	1	11	28	15	3	58	3.14
9	Secondary heating	0	0	1	0	0	1	3.00
10	Hot water	0	2	9	29	18	58	4.09
11	Lighting	9	10	21	6	12	58	3.03

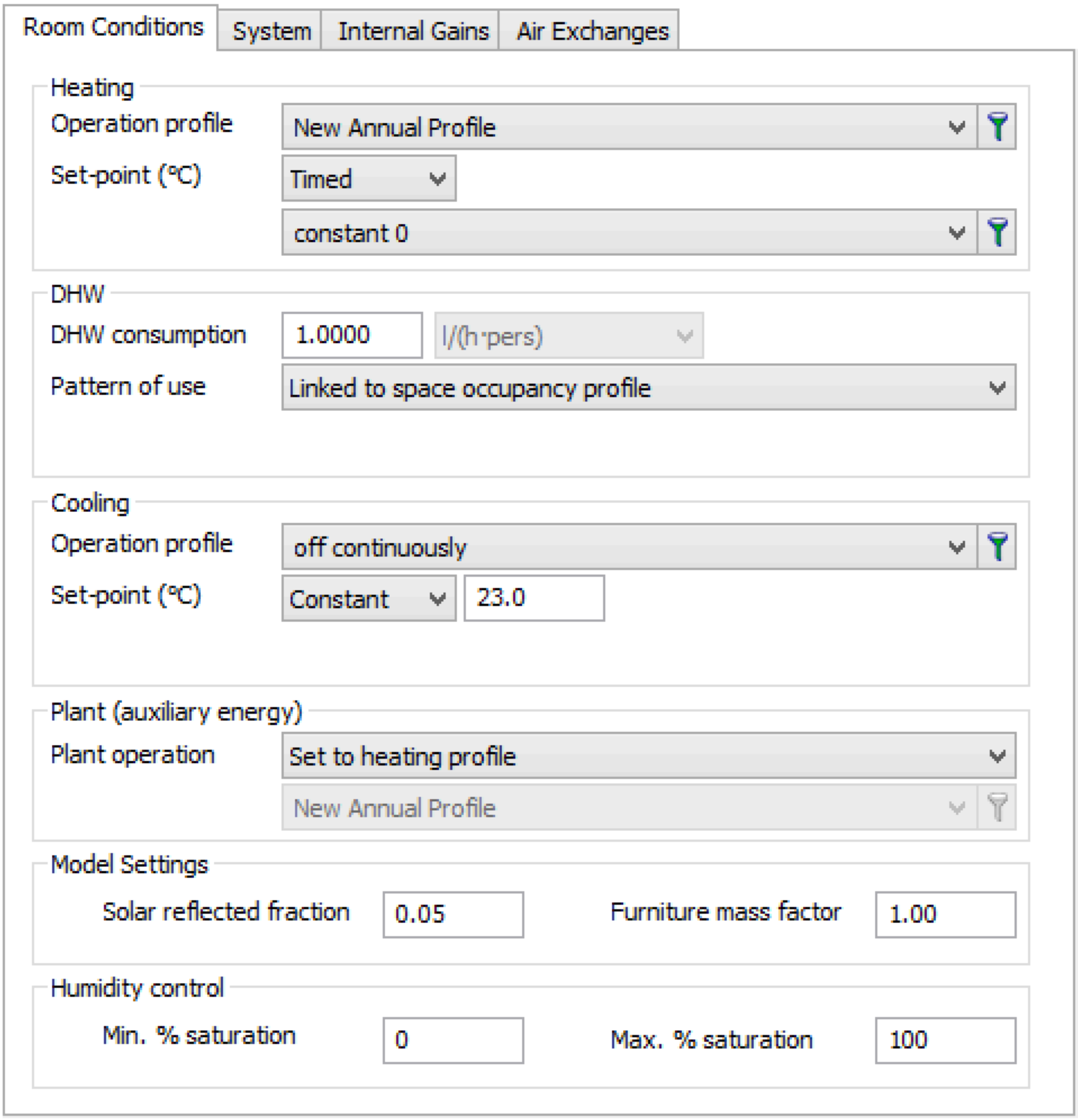
Statistic	Walls - a	Walls - b	Roof - pitched	Roof - room(s)	Windows	Main heating	Main heating controls	Secondary heating	Hot water	Lighting
Min Value	1	1	1	1	1	3	1	3	2	1
Max Value	5	4	5	4	5	5	5	3	5	5
Mean	2.26	2.90	2.51	2.98	2.53	4.29	3.14	3.00	4.09	3.03
Variance	2.93	1.29	1.71	1.70	1.41	0.25	0.72	0.00	0.61	1.75
Standard Deviation	1.71	1.14	1.31	1.30	1.19	0.50	0.85	0.00	0.78	1.32
Total Responses	58	21	41	44	58	58	58	1	58	58

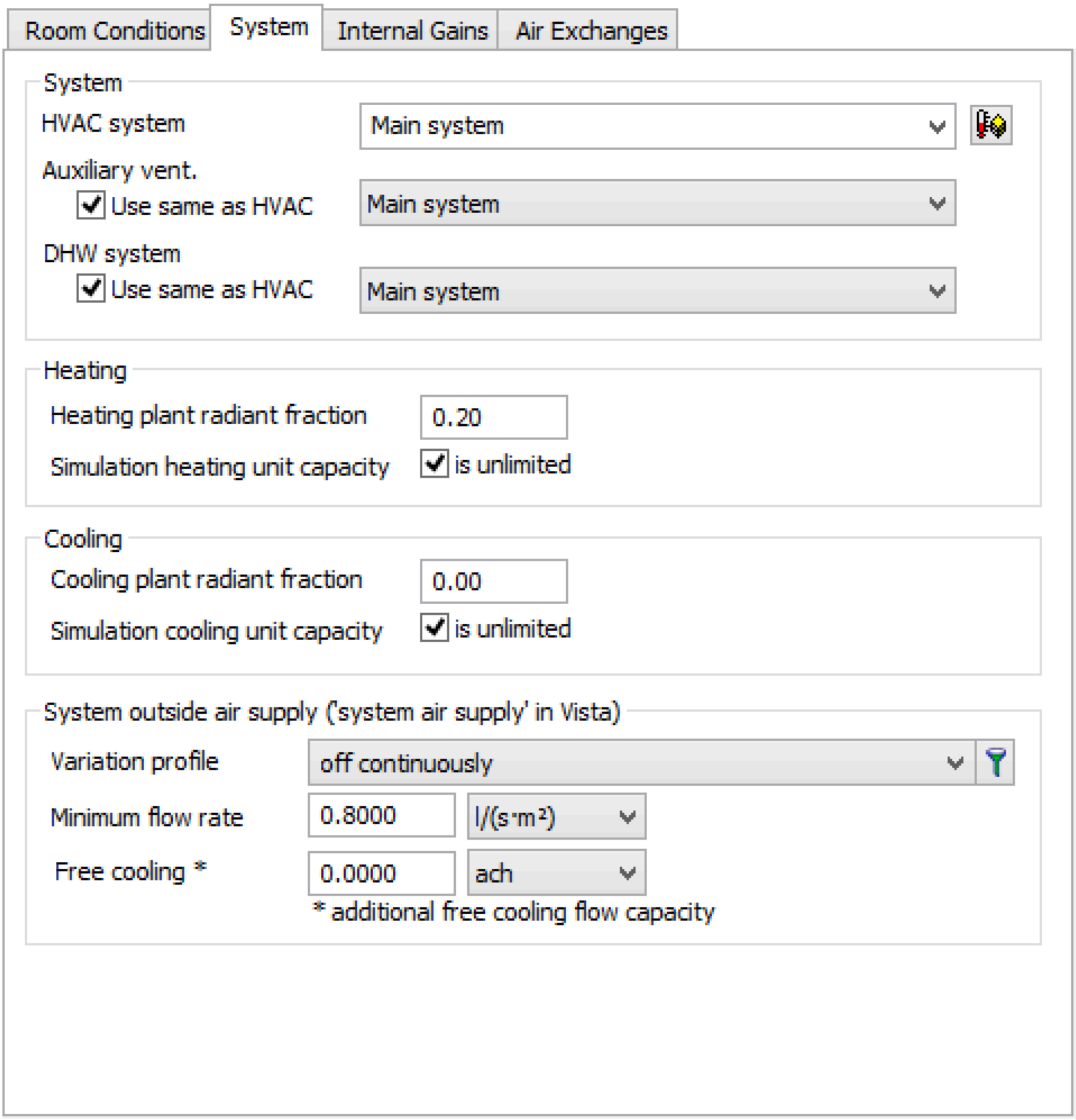
32. Dwelling orientation

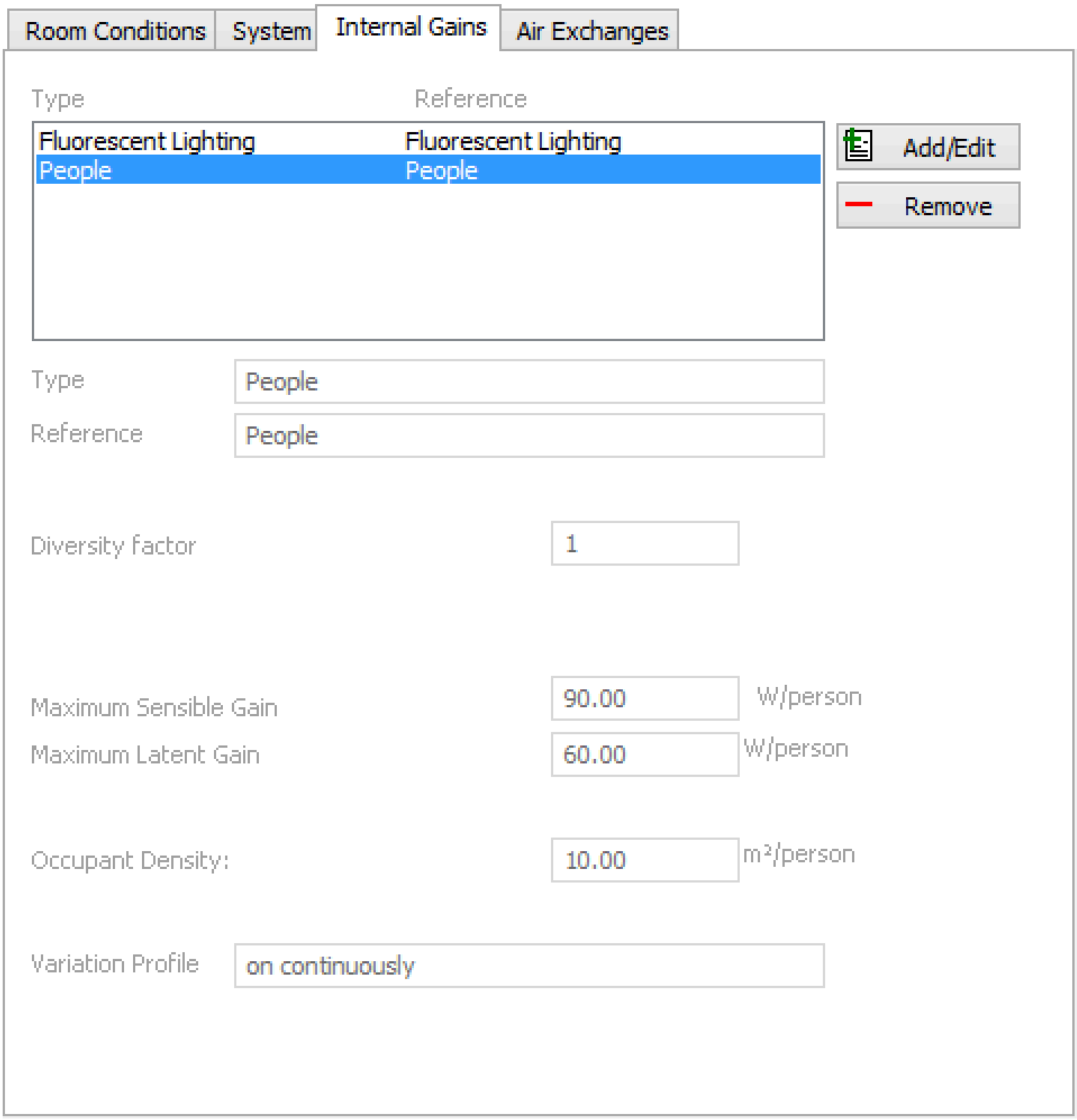
#	Answer		Response	%
1	South		6	8%
2	North		11	14%
3	East		10	13%
4	West		13	17%
5	South-East		7	9%
6	South-West		9	12%
7	North-East		5	6%
8	North-West		17	22%
	Total		78	100%

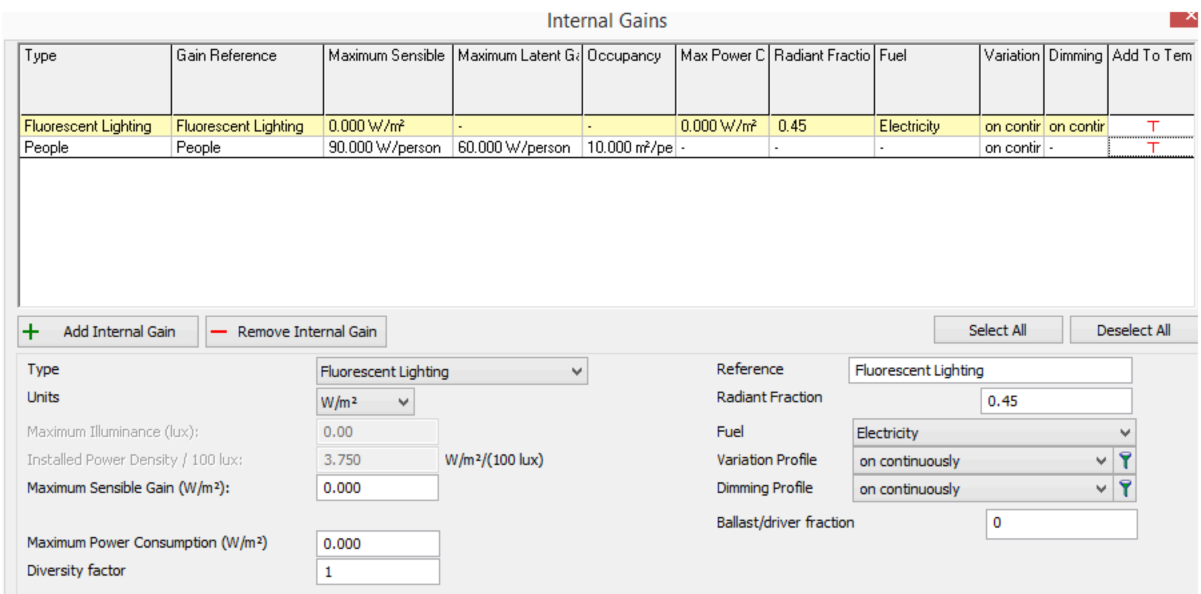
Statistic	Value
Min Value	1
Max Value	8
Mean	4.74
Variance	5.52
Standard Deviation	2.35
Total Responses	78

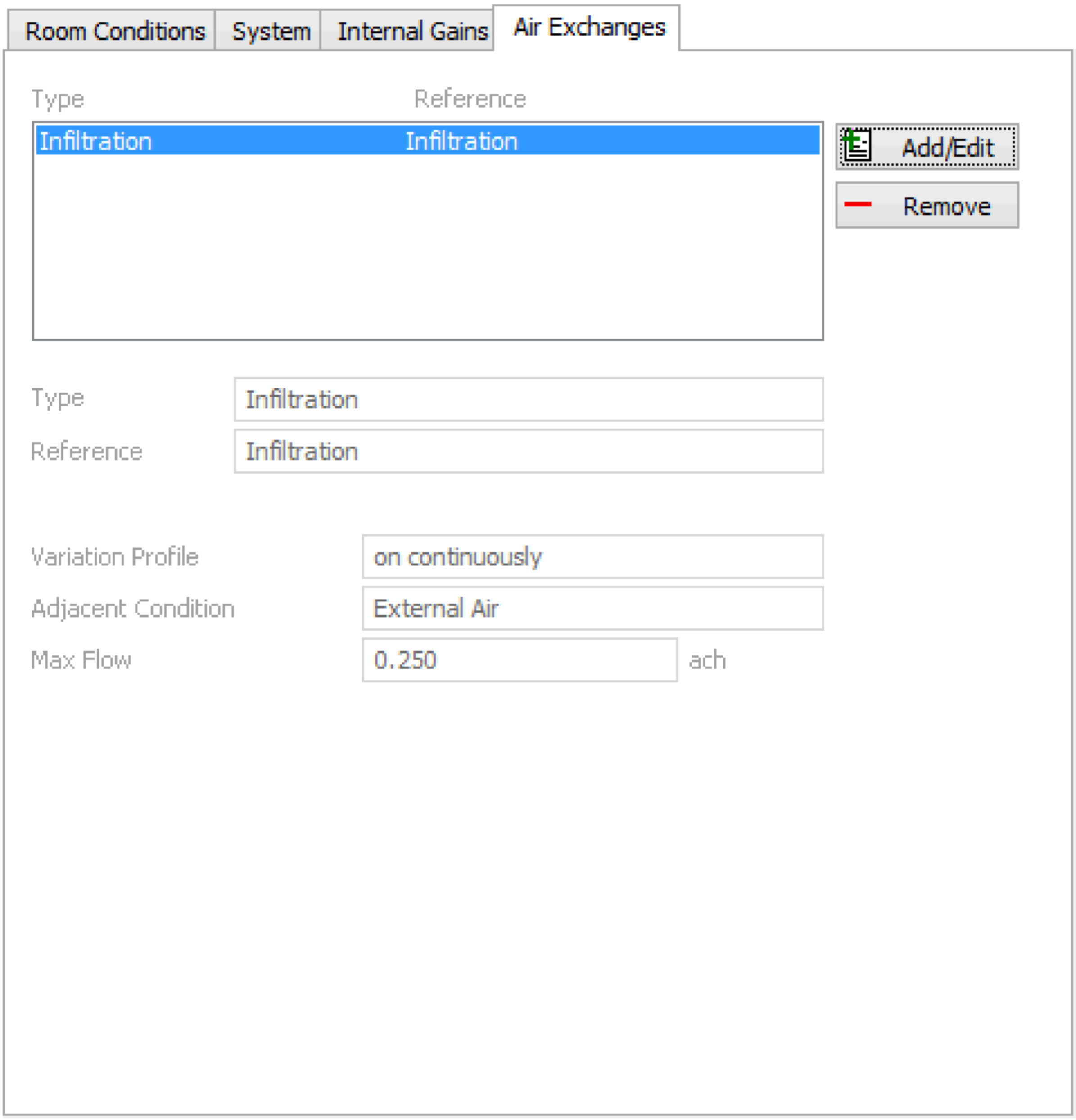
Appendix D Sample Input Data for Modelling

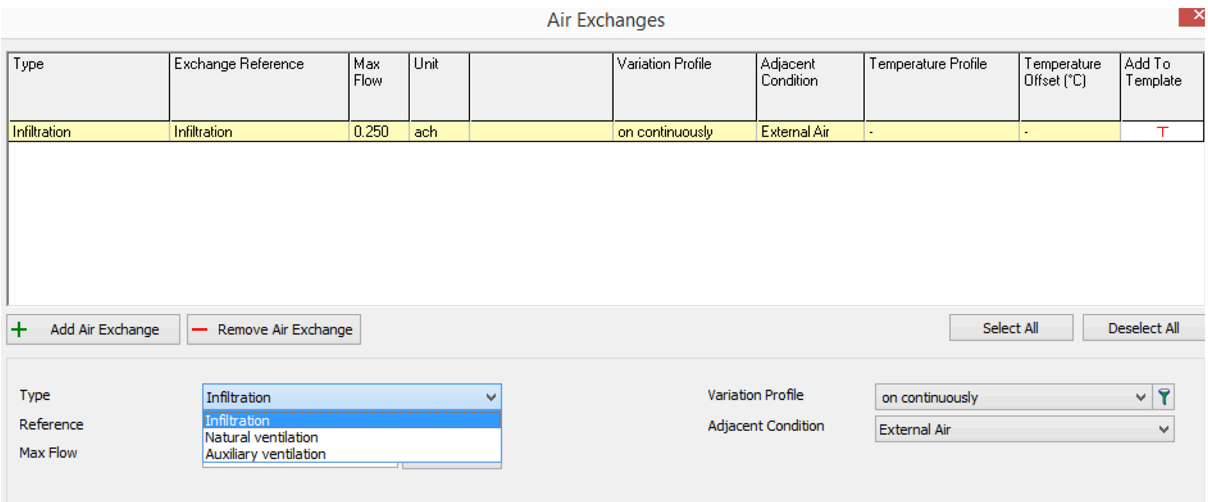


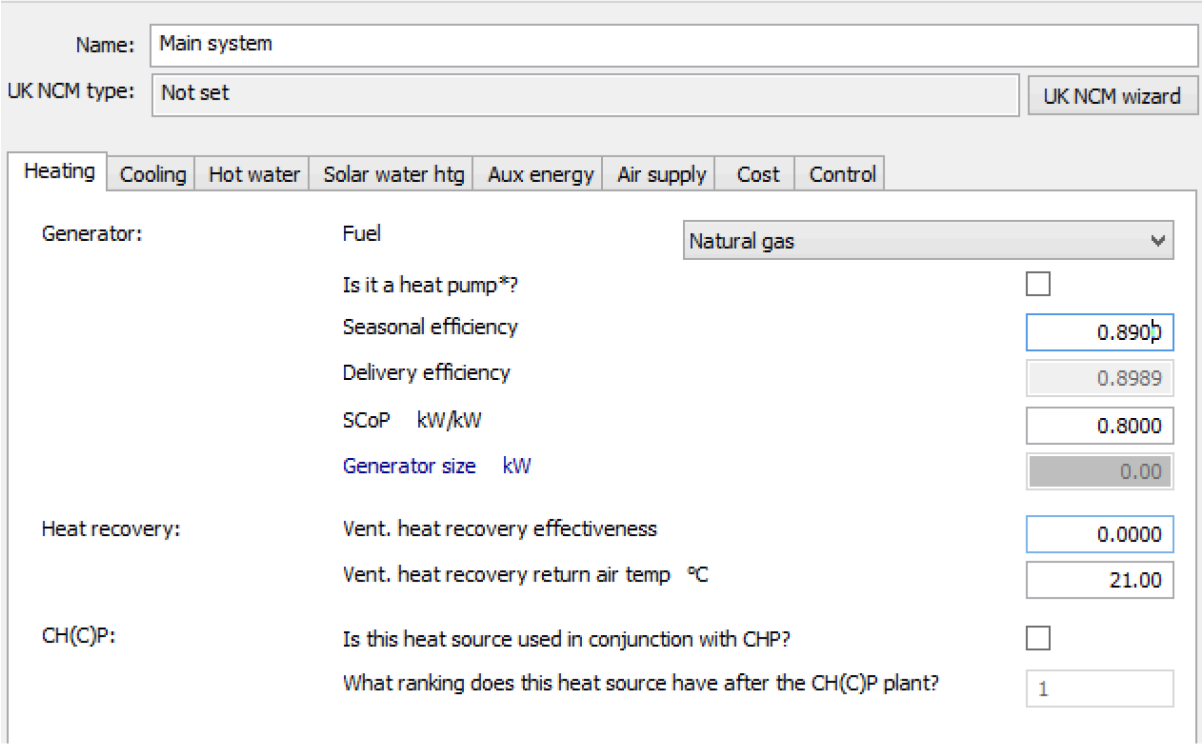

Room Conditions
System
Internal Gains
Air Exchanges
System
HVAC system
Main system
Auxiliary vent.
Use same as HVAC
Main system
DHW system
Use same as HVAC
Main system
Heating
Heating plant radiant fraction
0.20
Simulation heating unit capacity
is unlimited
Cooling
Cooling plant radiant fraction
0.00
Simulation cooling unit capacity
is unlimited
System outside air supply ('system air supply' in Vista)
Variation profile
off continuously
Minimum flow rate
0.8000
l/(s·m²)
Free cooling *
0.0000
ach
* additional free cooling flow capacity

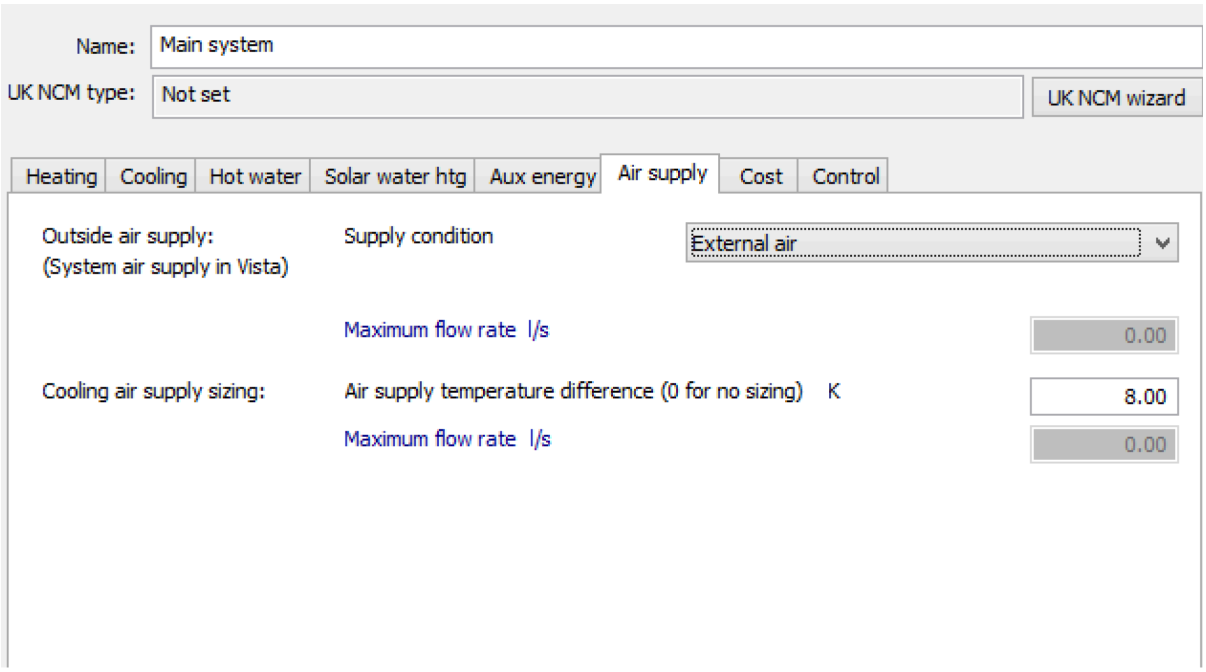

Room Conditions
System
Internal Gains
Air Exchanges
Type
Reference
Fluorescent Lighting
Fluorescent Lighting
People
People
Add/Edit
Remove
Type
People
Reference
People
Diversity factor
1
Maximum Sensible Gain
90.00
W/person
Maximum Latent Gain
60.00
W/person
Occupant Density:
10.00
m²/person
Variation Profile
on continuously

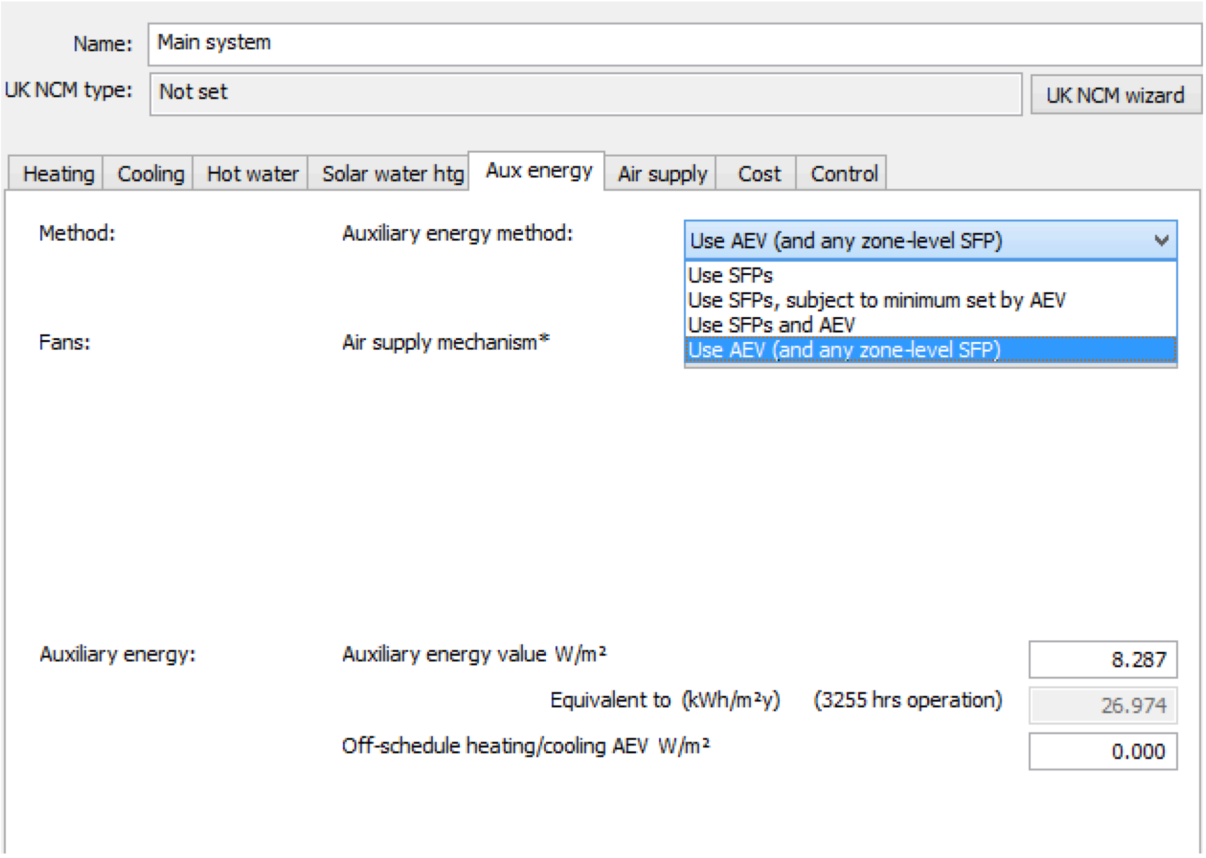

Internal Gains
Type
Gain Reference
Maximum Sensible
Maximum Latent Ga
Occupancy
Max Power C
Radiant Fractio
Fuel
Variation
Dimming
Add To Tem
Fluorescent Lighting
Fluorescent Lighting
0.000 W/m²
0.000 W/m²
0.45
Electricity
on contir
on contir
People
People
90.000 W/person
60.000 W/person
10.000 m²/pe
on contir
Add Internal Gain
Remove Internal Gain
Select All
Deselect All
Type
Fluorescent Lighting
Units
W/m²
Maximum Illuminance (lux):
0.00
Installed Power Density / 100 lux:
3.750
W/m²/(100 lux)
Maximum Sensible Gain (W/m²):
0.000
Maximum Power Consumption (W/m²)
0.000
Diversity factor
1
Reference
Fluorescent Lighting
Radiant Fraction
0.45
Fuel
Electricity
Variation Profile
on continuously
Dimming Profile
on continuously
Ballast/driver fraction
0

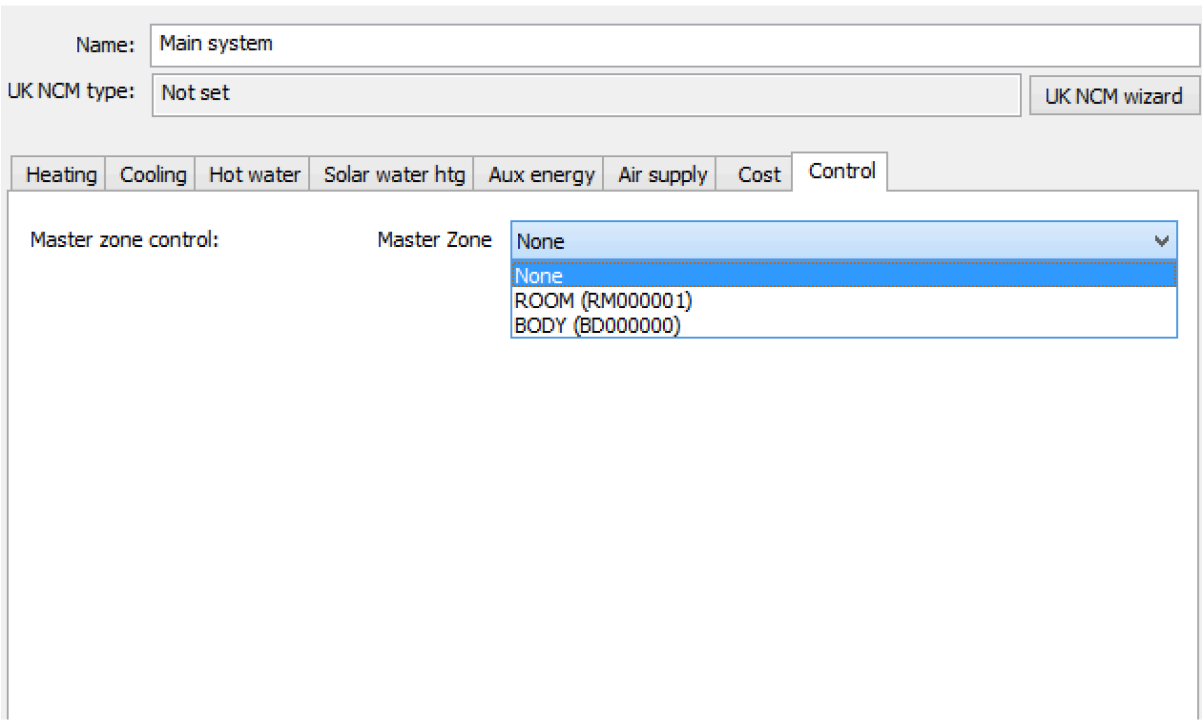

Room Conditions
System
Internal Gains
Air Exchanges
Type
Reference
Infiltration
Infiltration
Add/Edit
Remove
Type
Infiltration
Reference
Infiltration
Variation Profile
on continuously
Adjacent Condition
External Air
Max Flow
0.250
ach

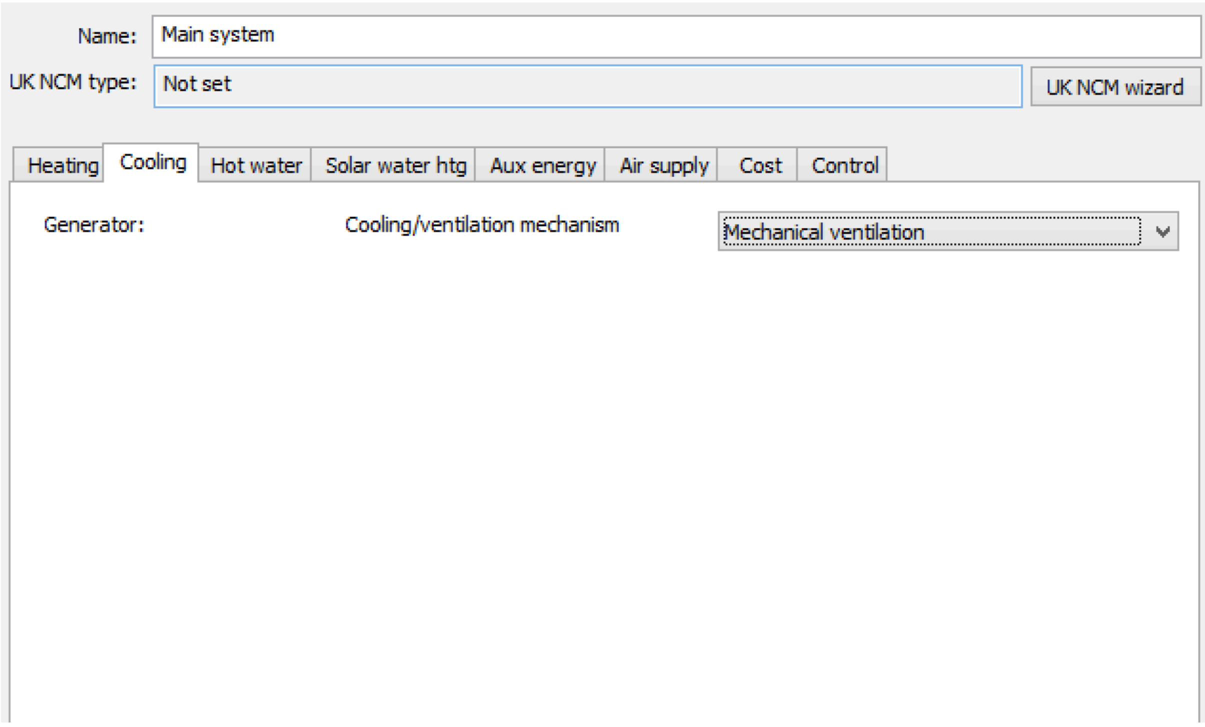

Air Exchanges
Type
Exchange Reference
Max Flow
Unit
Variation Profile
Adjacent Condition
Temperature Profile
Temperature Offset (°C)
Add To Template
Infiltration
Infiltration
0.250
ach
on continuously
External Air
Add Air Exchange
Remove Air Exchange
Select All
Deselect All
Type
Reference
Max Flow
Infiltration
Infiltration
Natural ventilation
Auxiliary ventilation
Variation Profile
on continuously
Adjacent Condition
External Air

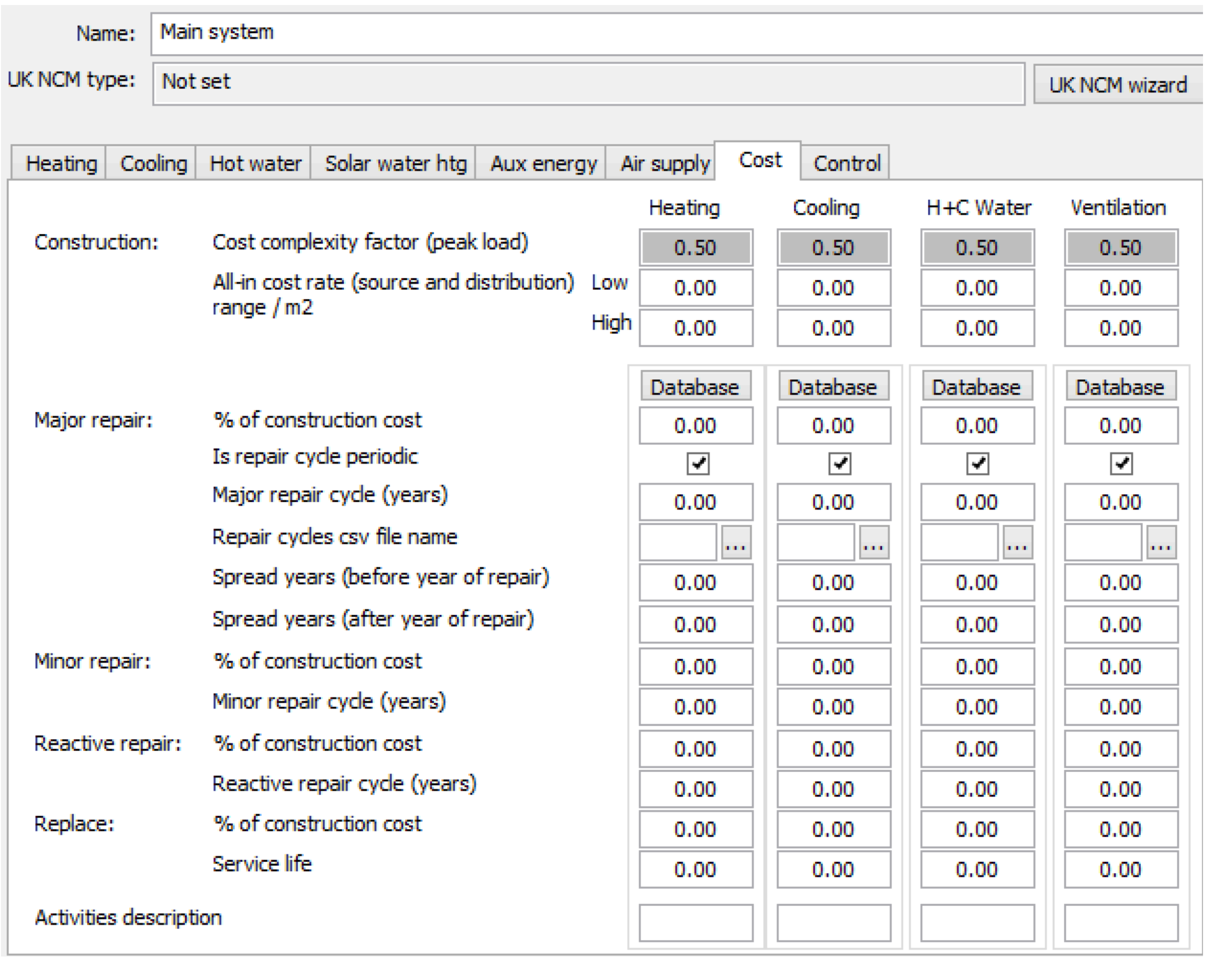

Name: Main system
UK NCM type: Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Generator:
Fuel
Natural gas
Is it a heat pump*?
Seasonal efficiency 0.8900
Delivery efficiency 0.8989
SCoP kW/kW 0.8000
Generator size kW 0.00
Heat recovery:
Vent. heat recovery effectiveness 0.0000
Vent. heat recovery return air temp °C 21.00
CH(C)P:
Is this heat source used in conjunction with CHP?
What ranking does this heat source have after the CH(C)P plant? 1

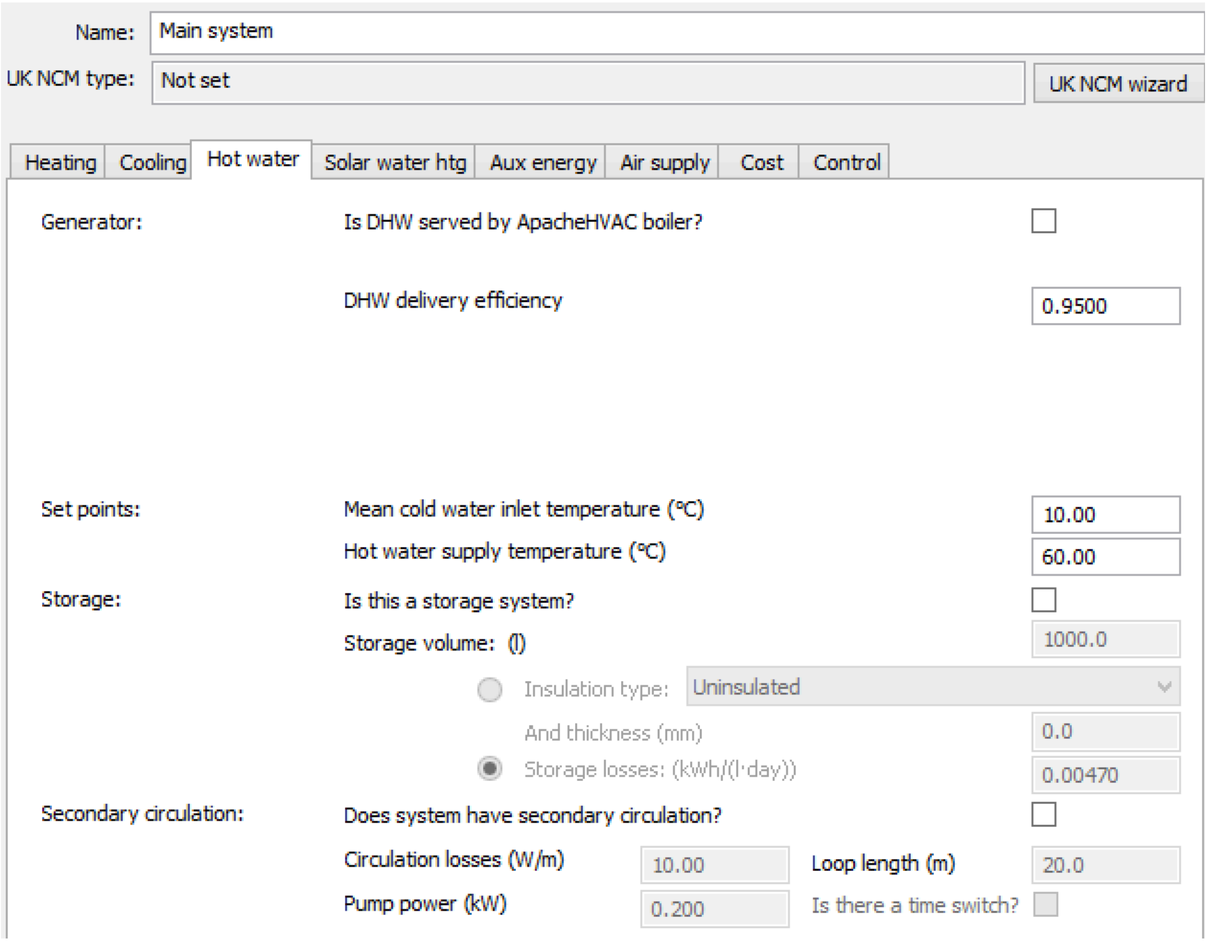

Name: Main system
UK NCM type: Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Outside air supply:
(System air supply in Vista)
Supply condition
External air
Maximum flow rate l/s 0.00
Cooling air supply sizing:
Air supply temperature difference (0 for no sizing) K 8.00
Maximum flow rate l/s 0.00

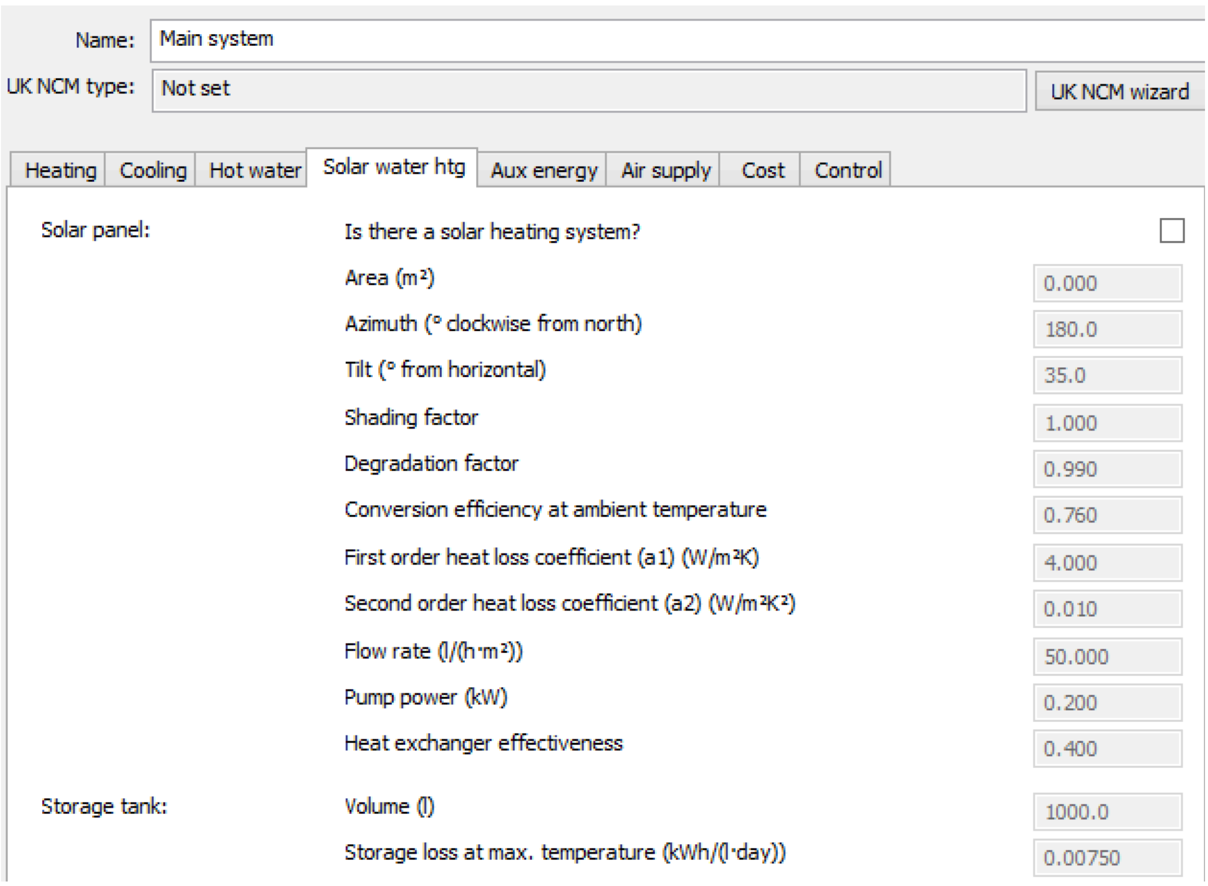

Name:
Main system
UK NCM type:
Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Method:
Auxiliary energy method:
Use AEV (and any zone-level SFP)
Use SFPs
Use SFPs, subject to minimum set by AEV
Use SFPs and AEV
Use AEV (and any zone-level SFP)
Fans:
Air supply mechanism*
Auxiliary energy:
Auxiliary energy value W/m²
8.287
Equivalent to (kWh/m²y)
(3255 hrs operation)
26.974
Off-schedule heating/cooling AEV W/m²
0.000

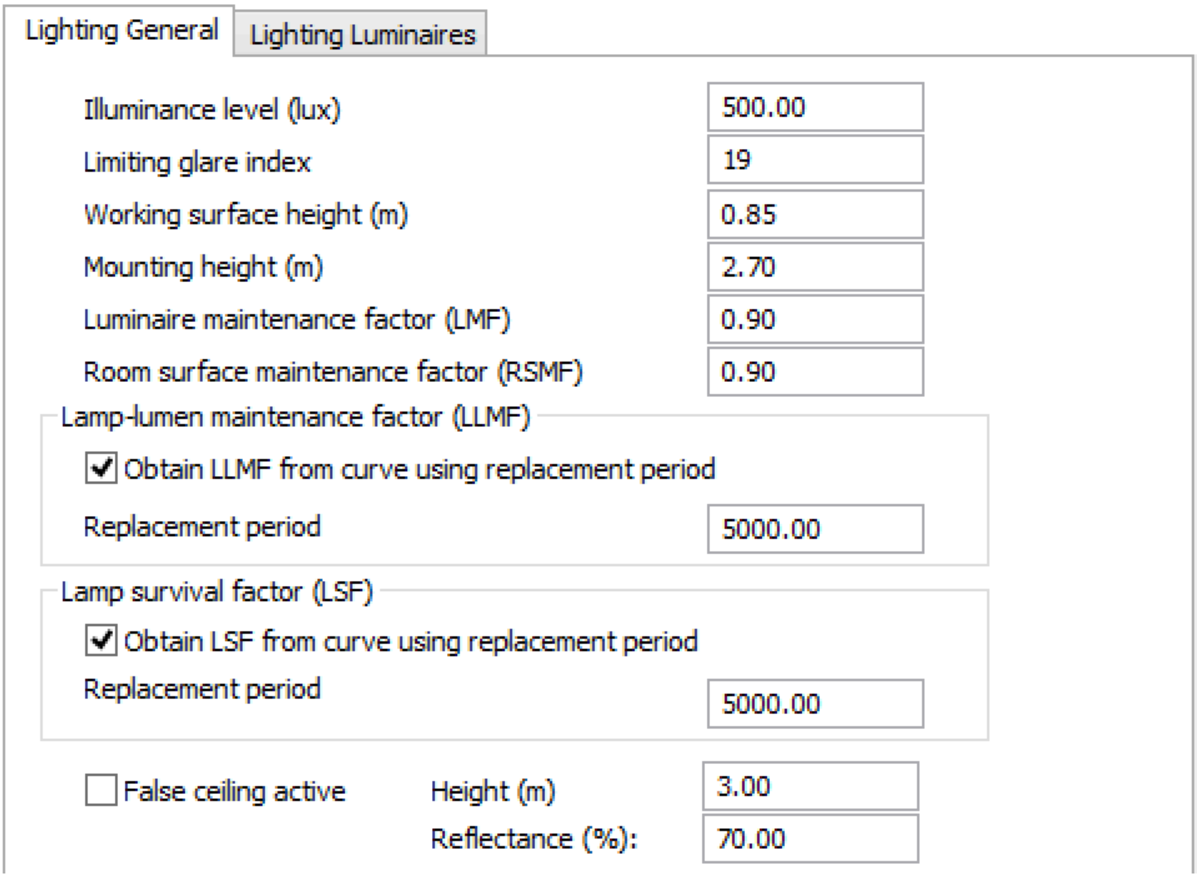

Name:
Main system
UK NCM type:
Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Master zone control:
Master Zone
None
None
ROOM (RM000001)
BODY (BD000000)

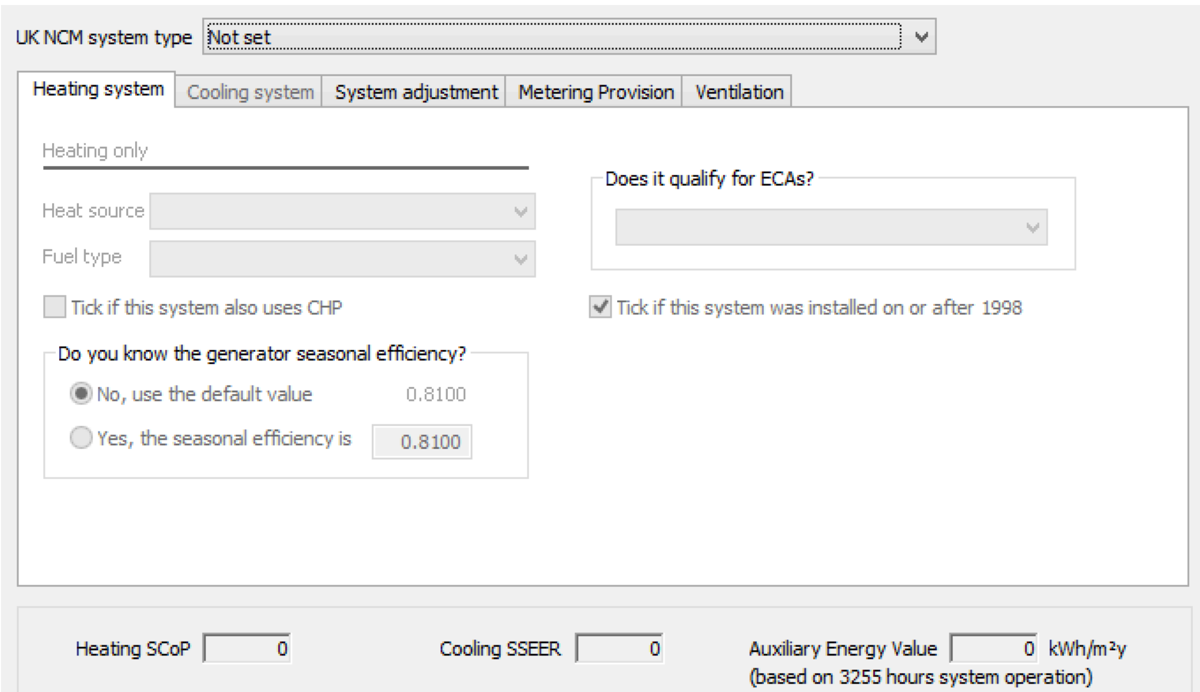

Name:
Main system
UK NCM type:
Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Generator:
Cooling/ventilation mechanism
Mechanical ventilation

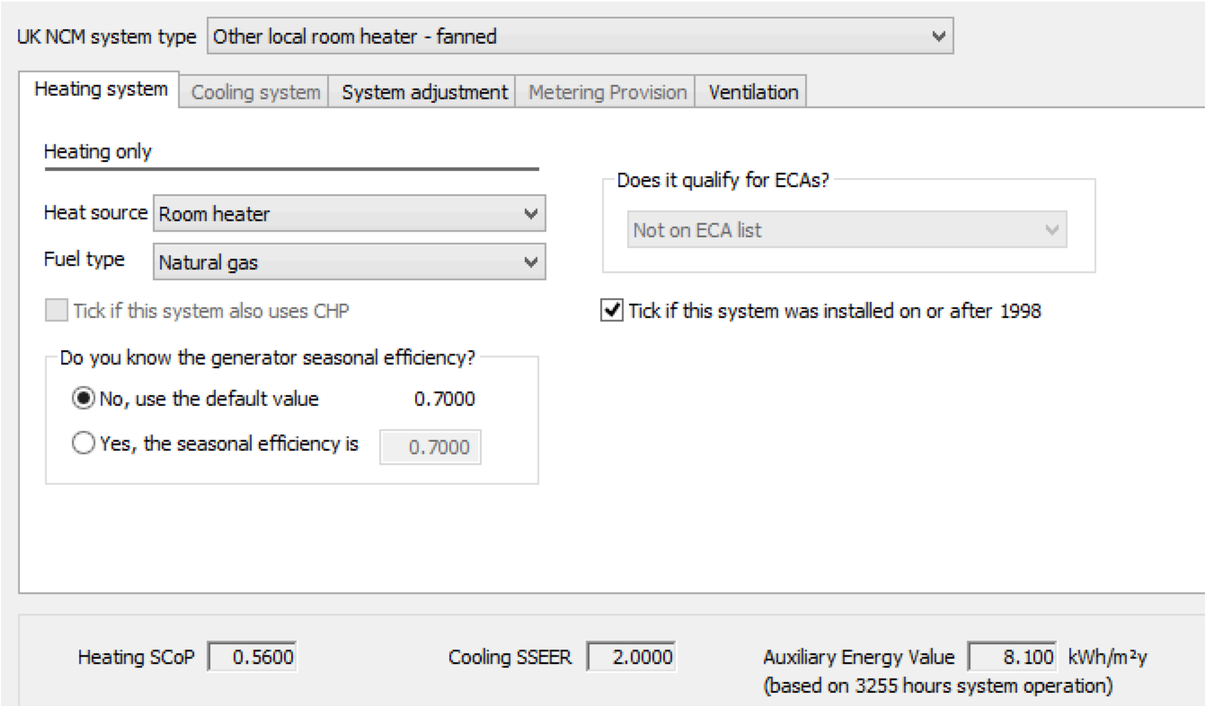

Name:
Main system
UK NCM type:
Not set
UK NCM wizard
Heating
Cooling
Hot water
Solar water htg
Aux energy
Air supply
Cost
Control
Heating
Cooling
H+C Water
Ventilation
Construction:
Cost complexity factor (peak load)
0.50
0.50
0.50
0.50
All-in cost rate (source and distribution) range / m2
Low
High
0.00
Database
Major repair:
% of construction cost
Is repair cycle periodic
Major repair cycle (years)
Repair cycles csv file name
Spread years (before year of repair)
Spread years (after year of repair)
Minor repair:
% of construction cost
Minor repair cycle (years)
Reactive repair:
% of construction cost
Reactive repair cycle (years)
Replace:
% of construction cost
Service life
Activities description

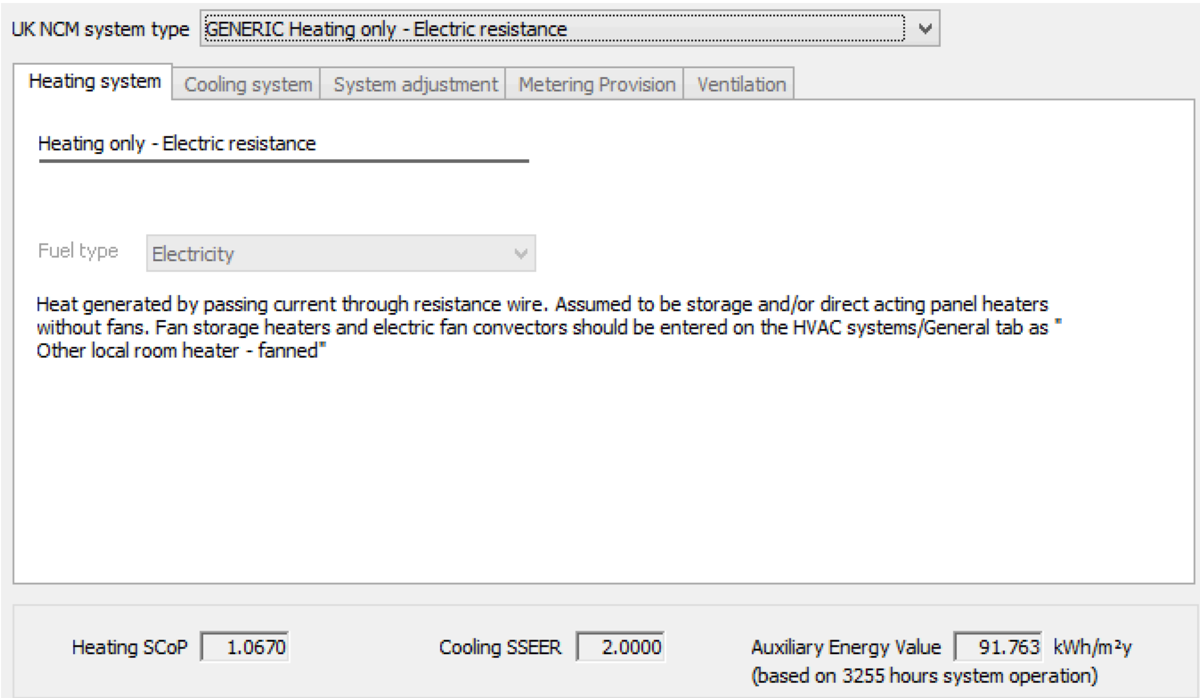

Name: Main system
UK NCM type: Not set
UK NCM wizard
Heating Cooling Hot water Solar water htg Aux energy Air supply Cost Control
Generator:
Is DHW served by ApacheHVAC boiler?
DHW delivery efficiency
0.9500
Set points:
Mean cold water inlet temperature (°C)
10.00
Hot water supply temperature (°C)
60.00
Storage:
Is this a storage system?
Storage volume: (l)
1000.0
Insulation type:
Uninsulated
And thickness (mm)
0.0
Storage losses: (kWh/(l·day))
0.00470
Secondary circulation:
Does system have secondary circulation?
Circulation losses (W/m)
10.00
Loop length (m)
20.0
Pump power (kW)
0.200
Is there a time switch?

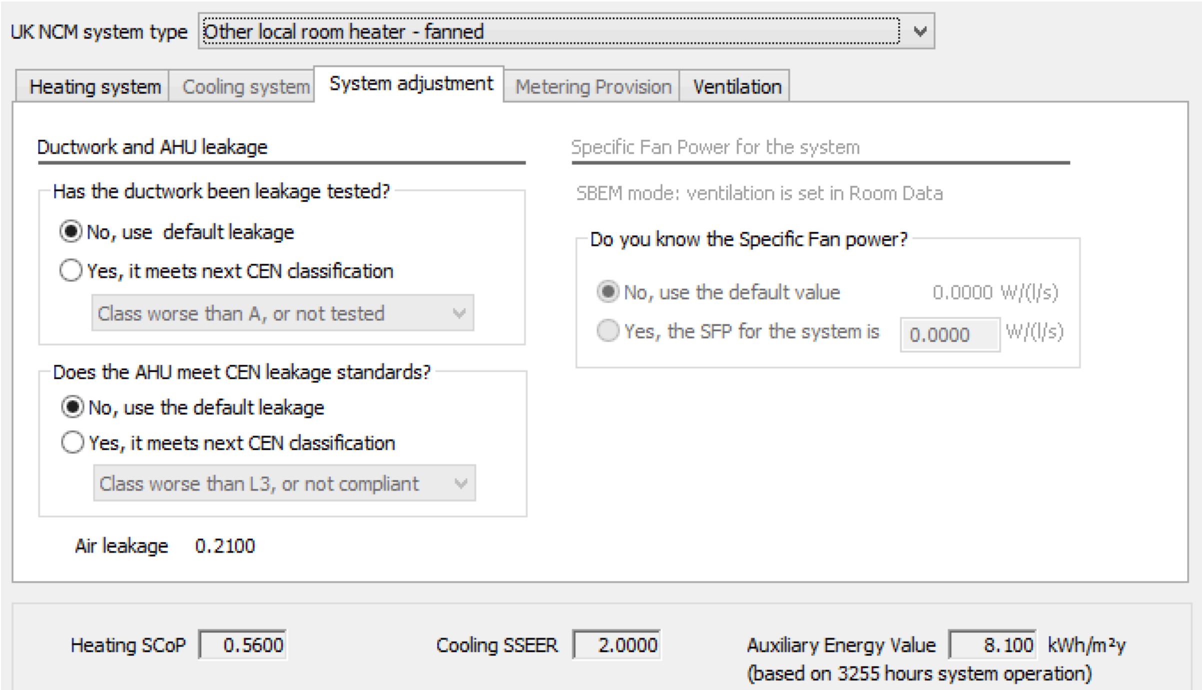

Name: Main system
UK NCM type: Not set
UK NCM wizard
Heating Cooling Hot water Solar water htg Aux energy Air supply Cost Control
Solar panel:
Is there a solar heating system?
Area (m²)
0.000
Azimuth (° clockwise from north)
180.0
Tilt (° from horizontal)
35.0
Shading factor
1.000
Degradation factor
0.990
Conversion efficiency at ambient temperature
0.760
First order heat loss coefficient (a1) (W/m²K)
4.000
Second order heat loss coefficient (a2) (W/m²K²)
0.010
Flow rate (l/(h·m²))
50.000
Pump power (kW)
0.200
Heat exchanger effectiveness
0.400
Storage tank:
Volume (l)
1000.0
Storage loss at max. temperature (kWh/(l·day))
0.00750

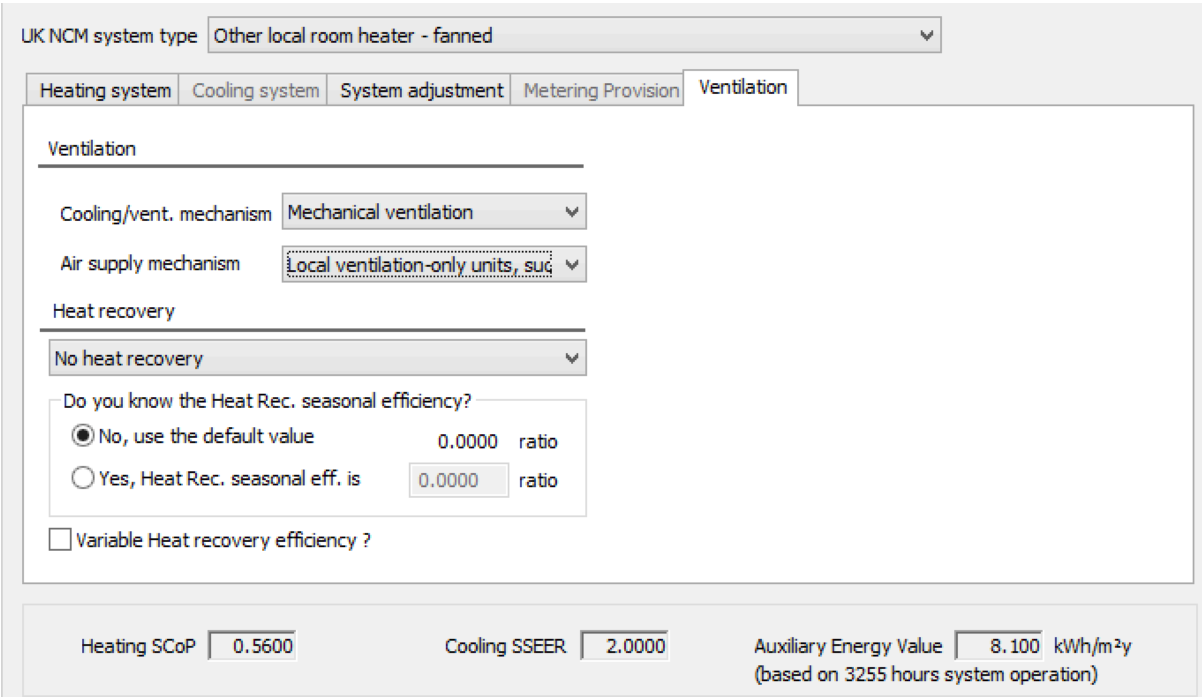

Lighting General
Lighting Luminaires
Illuminance level (lux)
500.00
Limiting glare index
19
Working surface height (m)
0.85
Mounting height (m)
2.70
Luminaire maintenance factor (LMF)
0.90
Room surface maintenance factor (RSMF)
0.90
Lamp-lumen maintenance factor (LLMF)
Obtain LLMF from curve using replacement period
Replacement period
5000.00
Lamp survival factor (LSF)
Obtain LSF from curve using replacement period
Replacement period
5000.00
False ceiling active
Height (m)
3.00
Reflectance (%):
70.00


UK NCM system type
Not set
Heating system
Cooling system
System adjustment
Metering Provision
Ventilation
Heating only
Heat source
Fuel type
Tick if this system also uses CHP
Does it qualify for ECAs?
Tick if this system was installed on or after 1998
Do you know the generator seasonal efficiency?
No, use the default value
0.8100
Yes, the seasonal efficiency is
0.8100
Heating SCoP
0
Cooling SSEER
0
Auxiliary Energy Value
0
kWh/m²y
(based on 3255 hours system operation)


UK NCM system type
Other local room heater - fanned
Heating system
Cooling system
System adjustment
Metering Provision
Ventilation
Heating only
Heat source
Room heater
Fuel type
Natural gas
Tick if this system also uses CHP
Do you know the generator seasonal efficiency?
No, use the default value
0.7000
Yes, the seasonal efficiency is
0.7000
Does it qualify for ECAs?
Not on ECA list
Tick if this system was installed on or after 1998
Heating SCoP
0.5600
Cooling SSEER
2.0000
Auxiliary Energy Value
8.100
kWh/m²y
(based on 3255 hours system operation)


UK NCM system type
GENERIC Heating only - Electric resistance
Heating system
Cooling system
System adjustment
Metering Provision
Ventilation
Heating only - Electric resistance
Fuel type
Electricity
Heat generated by passing current through resistance wire. Assumed to be storage and/or direct acting panel heaters without fans. Fan storage heaters and electric fan convectors should be entered on the HVAC systems/General tab as " Other local room heater - fanned"
Heating SCoP
1.0670
Cooling SSEER
2.0000
Auxiliary Energy Value
91.763
kWh/m²y
(based on 3255 hours system operation)


UK NCM system type
Other local room heater - fanned
Heating system
Cooling system
System adjustment
Metering Provision
Ventilation
Ductwork and AHU leakage
Has the ductwork been leakage tested?
No, use default leakage
Yes, it meets next CEN classification
Class worse than A, or not tested
Does the AHU meet CEN leakage standards?
No, use the default leakage
Yes, it meets next CEN classification
Class worse than L3, or not compliant
Air leakage 0.2100
Specific Fan Power for the system
SBEM mode: ventilation is set in Room Data
Do you know the Specific Fan power?
No, use the default value 0.0000 W/(l/s)
Yes, the SFP for the system is 0.0000 W/(l/s)
Heating SCoP 0.5600
Cooling SSEER 2.0000
Auxiliary Energy Value 8.100 kWh/m²y
(based on 3255 hours system operation)


UK NCM system type
Other local room heater - fanned
Heating system
Cooling system
System adjustment
Metering Provision
Ventilation
Ventilation
Cooling/vent. mechanism
Mechanical ventilation
Air supply mechanism
Local ventilation-only units, suc
Heat recovery
No heat recovery
Do you know the Heat Rec. seasonal efficiency?
No, use the default value 0.0000 ratio
Yes, Heat Rec. seasonal eff. is 0.0000 ratio
Variable Heat recovery efficiency ?
Heating SCoP 0.5600
Cooling SSEER 2.0000
Auxiliary Energy Value 8.100 kWh/m²y
(based on 3255 hours system operation)

Appendix E Research Ethics

E.1 Ethics Application

UNIVERSITY OF CAMBRIDGE

SCHOOL OF THE HUMANITIES AND SOCIAL SCIENCES

Application for ethical approval of a research project

Part I- Personal Information form- To be completed by the applicant

Question 1: Title of the study
Energy Efficiency and Comfort Practices: Interactions Between Building Technologies and Occupant Behaviour

Question 2: Primary applicant
Notes: The primary applicant is the name of the person who has overall responsibility for the study. Include their appointment or position held and their qualifications.
Hui Ben – PhD in Architecture **BArch(Hons) MA(Distinction) MPhil (Cantab)**

Question 3: Department and Contact Details of Primary applicant
Notes: Please include the department affiliation and also your contact details. This should also include the email address on which you wish us to contact you. Please note: If you don't have a departmental affiliation, please email cshssethics@admin.cam.ac.uk in the first instance, to get further information on how to proceed.

Department of Architecture
1-5 Scroope Terrace
Trumpington Street
Cambridge
CB2 1PX
Cambridge University
Hb403@cam.ac.uk

Question 4: Co-applicants

Notes: List the names of all researchers involved in the study. Include their departmental affiliations, appointment or position held and their qualifications. For research students, please include the name, department and contact details of your supervisor.

Dr Minna Sunikka-Blank
MSc Arch PhD
Senior University Lecturer
Department of Architecture
mms45@cam.ac.uk

Signatures of the study team

Notes: The primary applicant and all co-applicants must sign the form. For research students, the supervisor's signature is also required.

UNIVERSITY OF CAMBRIDGE

SCHOOL OF THE HUMANITIES AND SOCIAL SCIENCES

Part II- Application for ethical approval of a Research Project Pro forma
(To be completed by applicant for circulation to Ethics Committees)

1. Briefly describe the purpose of the research. (Please attach any detailed research proposal, if submitted or to be submitted for grant application)

The purpose of the research is to increase both energy saving and occupants' comfort through developing building design solutions, systems, technologies and interfaces that can assist users in developing an energy conscious behaviour together with a comfortable and healthy indoor environment.

2. Briefly describe the method and procedure. (Please attach interview schedules, questionnaires, etc). Include information about:
(a) personal questions, interview schedules, questionnaires
(b) duration and frequency of assessment sessions

This research utilizes several case studies in Cambridge to evaluate occupants' comfort experiences and everyday practices.

Methodologically it draws on Post Occupancy Evaluation with detailed monitoring and surveys of the selected occupants, using qualitative interviews to focus on actual practices in the everyday lives of the householders and build on different empirical possibilities of analysing households' comfort experiences and energy consumption. Five cases studies are proposed for deep interviews. In addition to interviews, the actual consumption (based on energy bills and data loggers etc.) is monitored. The monitored data is used to compare between what the interviewees say about their temperature and what they have actually consumed.

Then the case studies are used as the bases for the develop and test different ways of making typologies and understandings of users according to their energy consumption, practices, technologies and indoor climate.

3. Describe any discomfort or inconvenience to which participants may be subjected. Include information about:

(a) procedures that for some people could be physically stressful or might impinge on the safety of participants,

(b) procedures that for some people could be psychologically stressful.

(a) Sensors will be used to monitor internal temperature in chosen flats. These sensors will be placed in several different places inside the participants' rooms and might cause inconvenience.

(b) Interviews will be carried out and daily activities logs will be filled in by the participants which might cause stressfulness for some people.

4. (a) Who will the participants be?

(b) How will they be recruited?

(a) The participants will be selected from the residents/tenants in Cambridge.

(b) The participants will be recruited on personal connections.

5. Will participants be paid? If so, how much?

6. What will participants be told about the study? (Please attach a Participant Information Sheet)

(a) aims

(b) procedures

(a) Aims: increase both energy saving and occupants' comfort through developing building design solutions, systems, technologies and interfaces that can assist users in developing an energy conscious behaviour together with a comfortable and healthy indoor environment.

(b) Procedures: data will be collected from loggers used to monitor temperature and dairy logs used to record participants' daily activities.

7. What information about the research procedure or the purposes of the investigation will be withheld (if anything)?

No procedure or the purposes of the investigation will be withheld.

8. When will consent be obtained? (Please attach a Participant Consent form, written on headed paper and including your name(s), address and contact phone number.)
(a) Prior to the investigation? OR At the time of the investigation?
(b) Will consent be verbal OR written OR electronic via computer? (if not written, please justify this)
(c) Will consent be personal OR third party on behalf of the participant?
(d) Will personally identifiable information be made available beyond the research team? If so, to whom, and how will consent be obtained for use of personal information?

(a) The consent will be obtained prior to the investigation.
(b) The consent will be in written format and signed by the participant.
(c) The consent will be personal.
(d) The personally identifiable information will not be made available beyond the research team.

9. At the end of the research, what will participants be told about the investigation? Include (a) debriefing, (b) ways of alleviating any distress that might be caused by the study and (c) ways of dealing with any problem relating to the focus of the study that may arise.

All participants involved will asked if they would like to be provided with the conclusions and outcomes of the research. On completion of the study, those participants who request this information shall be provided with a one page PDF summary and the opportunity to access published material.

10. Has the person carrying out the project had previous experience of the procedures to be used? If not, who will supervise that person?

The primary applicant responsible for carrying out the research has direct experience of the sensor based monitoring. The researcher has gained previous experience of POE study from MPhil by Research at University of Cambridge. This research project is supervised by Dr Minna Sunikka-Blank.

11. Public indemnity insurance would normally be provided by the University's insurance for persons employed by them or working in their institutions. If you do not have appropriate institutional affiliation, how will you provide public indemnity insurance, including insurance against non-negligent injury to participants?

12. If data is to be analysed or stored on a computer, you must make arrangements to comply with the Data Protection Act (see your Departmental Data Protection Officer). Have you done this? Also, how do you intend to store data and for how long?

Arrangements have been made to comply with the Data Protection Act. All data will be depersonalized and stored in password-protected folders on the personal laptop of the researcher, during the study. This data will not be duplicated away from this station and shall also benefit from Firewall protection. After the study is completed, all participants' personal data shall be deleted. The researcher will not keep the copies of participant logs, as these will be retained by the participants, following the retrospective interviews.

13. Research conducted by students:

- **a. Has the student received appropriate training in conducting research with these subjects?**
- **b. Please outline the involvement of the supervisor in overseeing the conduct of this research?**
- **c. The Committee assume that any application relating to a research or investigation project which forms part of a taught course has been discussed with the Head of Department. Please enclose confirmation from the Head of Department which will then be sent to the Ethics Committee.**

a. **The primary applicant has been trained as an architecture student with Bachelor of Architecture (Hons), MA in Architecture (Distinction), and MPhil in Architecture by Research (Cantab).**
b. **The process of this research will be reported to the supervisor twice a month.**
c. **The confirmation from the Head of Department is enclosed.**

14. Signature(s) of applicant(s). It is important that all applicants named in point 1 sign below:

CHECK-LIST OF THINGS TO ENCLOSE WITH THE APPLICATION

Please note that this is only a list of essential documents that would be required for the consideration of your application by the committee. Please attach any further documentation that you think might help the committee in reaching a decision about your application.

- Detailed Research Proposal
- Questionnaire Survey
- Participant Information Sheet
- Participant Consent Form
- For Students: A signed letter from the Head of Department confirming that they are happy for you to go ahead with the research intended.

Date of application: 02 Dec 2012

Please return completed form to Humanities and Social Sciences Research Ethics Committee, School of the Humanities and Social Sciences, 17 Mill Lane, Cambridge CB2 1RX.

E.2 Ethical Approval Letter

UNIVERSITY OF CAMBRIDGE
School of the Humanities and Social Sciences

Ms Tamara Hug
Ethics Committee Secretary

Ms Hui Ben
Department of Architecture
1-5 Scroope Terrace
Trumpington Street
Cambridge
CB2 1PX

19 December 2013

Dear Hui

Ethical approval: Energy Efficiency and Comfort Practices: Interactions between Building Technologies and Occupant Behaviour

The Ethics Committee for the School of the Humanities and Social Sciences has considered the documentation you provided, which followed the procedures concerning ethical approval of research.

I am able to inform you that approval, with respect to ethical considerations, has now been given to your project. Please note that this clearance is based on the documentation you have submitted. You must resubmit your application to the Ethics Committee should you subsequently make any substantive changes relating to matters reviewed by the Committee.

With best wishes

Yours sincerely

I. Humphreys

p.p.
Tamara Hug
Ethics Committee Secretary

cc Dr Sunikka-Blank, Department of Architecture

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Cambridge CB2 1RX
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